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Transport impacts on atmosphere and climate: Land transport

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A B S T R A C T

Emissions from land transport, and from road transport in particular, have significant impacts on the atmosphere and on climate change. This assessment gives an overview of past, present and future emissions from land transport, of their impacts on the atmospheric composition and air quality, on human health and climate change and on options for mitigation.

In the past vehicle exhaust emission control has successfully reduced emissions of nitrogen oxides, carbon monoxide, volatile organic compounds and particulate matter. This contributed to improved air quality and reduced health impacts in industrialised countries. In developing countries however, pollutant emissions have been growing strongly, adversely affecting many populations. In addition, ozone and particulate matter change the radiative balance and hence contribute to global warming on shorter time scales. Latest knowledge on the magnitude of land transport's impact on global warming is reviewed here.

In the future, road transport's emissions of these pollutants are expected to stagnate and then decrease globally. This will then help to improve the air quality notably in developing countries. On the contrary, emissions of carbon dioxide and of halocarbons from mobile air conditioners have been globally increasing and are further expected to grow. Consequently, road transport's impact on climate is gaining in importance. The expected efficiency improvements of vehicles and the introduction of biofuels will not be sufficient to offset the expected strong growth in both, passenger and freight transportation. Technical measures could offer a significant reduction potential, but strong interventions would be needed as markets do not initiate the necessary changes. Further reductions would need a resolute expansion of low-carbon fuels, a tripling of vehicle fuel efficiency and a stagnation in absolute transport volumes. Land transport will remain a key sector in climate change mitigation during the next decades.

1. Introduction

1.1. Scope and structure of this publication

This is an international assessment of the impacts of land transport on climate and atmospheric composition within the European 6th Framework project 'ATTICA' publication series (Transport Impacts on Atmosphere and Climate). Further assessments give an overview of Metrics for estimating emission impacts at different time scales (Fuglestvedt et al., 2010), aviation impacts on atmosphere and climate (Lee et al., 2010) and shipping impacts on atmosphere and climate (Eyring et al., 2010).

Emissions from land transport, coming primarily from road vehicles and to a smaller extent from rail and inland shipping, dominate the release of long-lived greenhouse gases from transportation. They make a major and increasing contribution to the total anthropogenic greenhouse effect. Furthermore, many

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short-lived gases and particles are emitted by land transport, which have an impact on atmospheric composition and air quality. This report relies on peer-reviewed literature, selected studies of the recent years and research carried out in the European *Quantify* project in order to assess what we know about this increasingly important role of land transport. According to the concept of this publication, we give answers to the questions: What is emitted? What are the impacts on the atmosphere? What are the impacts on the radiation budget and climate change? Which responses and future developments are likely?

After an introduction and view back in chapter 1, we give in chapter 2 an overview of the different types of direct and indirect emissions. This includes long-lived as well as short-lived emissions, released by land transport vehicles on a global scale and partially in comparison of industrialised and developing regions. The briefly discussed chemistry of active species such as ozone (O_3) nitrogen oxides (NO_x), carbon monoxide (CO) or non-methane volatile organic compounds (NMVOC) have an impact on atmospheric composition which is presented as a result of global models in chapter 3. These species or particles or both together have also an impact on air quality and health which is summarised in the same section. In particular carbon dioxide and ozone, but to a non-negligible extent also halocarbons have an influence on radiative forcing and the climate system. This is discussed in chapter 4. Finally, we present in chapter 5 (future developments) evolving trends in vehicle technology, alternative fuels and mobility management and assess their potential to reduce emissions. In different emission scenarios we give an outlook to the future, although the respective calculations of future climate impacts are still part of ongoing research.

1.2. *Land transport from the past to the present*

Many people associate an increase in their personal mobility with an increase in life quality. From the time of ancient civilizations up to about 250 years ago, the power to overcome long distances came from horses, donkeys, cattle, camels or human muscles. Nowadays climate science considers the period of the development of steam engines allowing to convert the energy of fossil fuels into the movement of a wheel (e.g. by James Watt in 1769) as the end of the pre-industrial time and as the start of a significant human alteration of the natural greenhouse effect. These engines, based on fossil fuels, did not only initialise the start of the industrial revolution but also of modern transport. First they were applied in ships and trains. Between 1900 and 1930 it is likely that shipping was still the largest source of CO_2 emissions from the transport sector (Fuglestvedt et al., 2008).

Since ships and rail were first the dominating emitters they still have a relatively higher relevance in cumulative CO_2 than in present emissions as shown in Table 1. But after 1910 road traffic gained soon more and more importance, overtaking all other transport modes. Fig. 1 demonstrates the enormous increase in road vehicles, which are now responsible for typically 75–80% of all CO_2 emissions from transport.

The car fleet in the United States grew from about 140,000 vehicles in 1907 to more than 20 million in 1927. A similar development took place in Europe with a delay of about 30 years, i.e. after the second world war. Still in 1960, there were less than 10 cars per 1000 inhabitants in United Kingdom, growing up to about 400 and more within 40 years and boosting the usage of oil. Now, again with a shift of 30 years, a similar evolution starts in East Asia. The permanently increasing fuel consumption in road transport will soon generate more than one fifth of the global CO_2 emissions.

Shorter-lived exhaust gases from dense road traffic had and have negative impacts on air quality. Road vehicles are a major source of nitrogen oxides over land. The induced photochemical smog is often mixed with particle emissions and was called 'ozone smog' or Los Angeles smog. It was first discovered in Los Angeles and soon attributed to the dense road traffic in the 1940th and 1950th. Maximum concentration observed in L.A. was 580 ppb (1160 $\mu g\ m^{-3}$) of ozone. An answer to the problem was the regulation of car emissions which began with the U.S. Clean Air Act of 1970. Mass production of catalytic converters started for the 1975 car generation in the U.S. About one decade later it was introduced also in Europe.

Road transport became more and more important not only for private passenger vehicles, but also in the cargo business. Vans were more flexible than trains or ships and the continuously improving state of the road infrastructure increased their mobility. The share of road transport in the European inland freight transport markets in tonne kilometres of freight reached 78% in 2004 (EEA member countries). The total freight volume increased by 43% between 1992 and 2005 (EEA report No. 1/2007).

Gradually, increasing attention has been paid to road transport as a health problem. Due to stricter legislation and improved reduction technologies emissions could be reduced in the recent two decades. Following near stagnation during the 1970s and 1980s, the emissions of carbon monoxide (CO) and non-methane volatile organic compounds (NMVOC) fell by a factor of two to three in 10 years in many European countries. Also nitrogen oxide (NO_x) and particulate matter (PM) emissions fell after a peak around 1990, although the problem of increasing NO_2 emissions from diesel vehicles with particle filters still requires improved technologies in order to achieve continued reductions.

Carbon dioxide emissions continued to increase despite improved fuel efficiency. Increasing mileage and comfort (e.g. air conditioners) as well as larger and more powerful vehicles more

Table 1
Emissions of CO_2 from transport in year 2000 and cumulative emissions 1900–2000. Derived from calculations condensed in Fuglestvedt et al. (2008).

	2000		Cumulative 1900–2000	
	Emissions Tg CO_2	Share [%]	Emissions Tg CO_2	Share [%]
Road	4282	72.3	114,494	55.1
Rail	124	2.1	20,913	10.1
Maritime shipping	626	10.6	31,940	15.4
Aviation	688	11.6	16,890	8.1

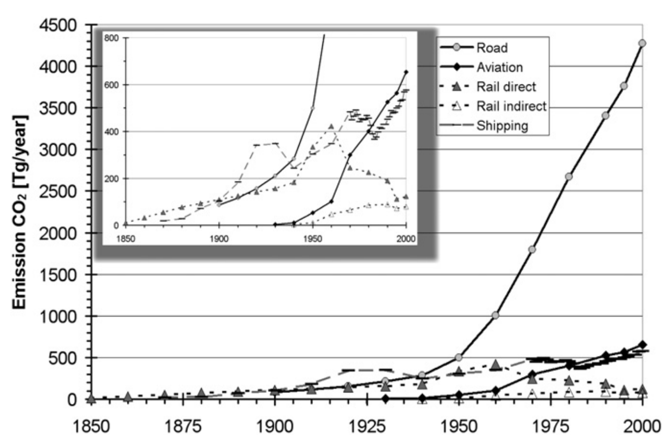

Fig. 1. CO_2 emissions from the transport sector 1900–2000 (from Fuglestvedt et al., 2008). The inset shows the lower values with a higher resolution of the *y*-axis.

than outweighed the progress made in engine technologies. The example in Fig. 2 of the development in France, representative of many countries in Western Europe, illustrates this trend.

The situation is slightly different for the United States, where large cars were already common in the past. Due to higher engine efficiency and smaller vehicles the fuel used per vehicle does not increase anymore. But the number of registered vehicles and the total amount of motor fuel consumed did not yet reach a saturation point.

While the so far dominating European and North American regions could not yet achieve a reduction of their fuel consumption, a very strong growth is observed in many developing countries. Therefore land transport emissions continue to be a major burden for the environment. The analysis of the present situation and the estimation of future developments are subject of numerous scientific publications and several assessments. An overview of major studies and recent research is also given in Appendix A.

2. Land transport emissions

2.1. Exhaust emissions of road transport

There are few recent estimates of road transport's global fuel consumption and related CO_2 emissions (IEA, 2004, 2005a,b; IEA/OECD, 2006; Turton, 2006) and a few estimates include non-CO_2 exhaust emissions (Aardenne et al., 2005; Borken et al., 2007; Fulton and Eads, 2004). At the level of regions and countries more emission inventories are available and the level of detail in both, approach and results, usually increases strongly. Here, we first discuss the global emission totals and then briefly analyse emissions in North America, Western Europe and developing Asia as the most relevant regions.

All global emission estimates take the road fuel consumption as given by the International Energy Agency as a reference (e.g. IEA, 2004, 2005a,b): Aardenne et al. (2005) have taken the amount of fuel consumed as starting point and multiplied with fuel specific emission factors (Tier 1 approach, cf. IPCC, 2006). Fulton and Eads (2004) and Borken et al. (2007) have calibrated their vehicle mileage to the year 2000 fuel consumption (Tier 2 approach). Borken et al. (2007) cross-checked with national data and calculated the fuel consumption bottom-up notably for China, Iran, Saudi-Arabia, Russia and India as well as many smaller countries in Africa and Latin America. They conclude on misallocation of the statistical entries, under- or non-reporting notably of the diesel fuel consumption and derive a global diesel fuel consumption of 550 Mtoe, about 6% higher than reported by IEA energy statistics for that year. About 38% of the 1450 Mtoe total fuel consumed is diesel, 60% is gasoline, gaseous fuels and liquid biofuels account for about 1% and 0.7% respectively. In consequence, all global emission estimates assume about the same amount of fossil fuel and calculate about the same global CO_2 emissions.

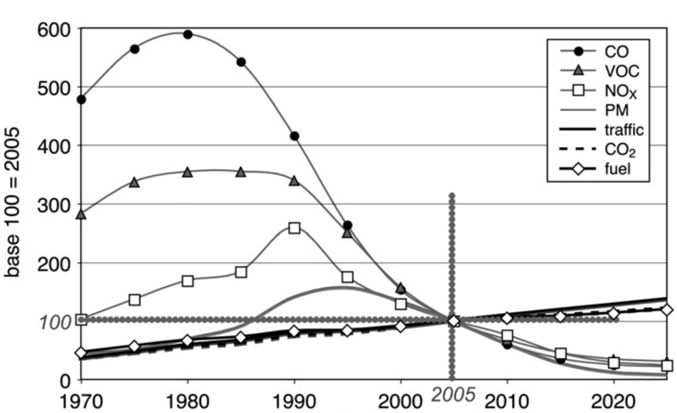

Fig. 2. Relative evolution of mileage and emissions of French road-traffic emissions from 1973 to 2020. Base 100 = year 2005 (Joumard, 2005).

Differences are much stronger for the non-CO_2 emissions because of the different assumptions how the mileage is distributed among the different vehicle categories and what the average exhaust emission factors are. Both, Borken et al. (2007) and Fulton and Eads (2004) have differentiated by 5 vehicle categories and several fuel types and the emission factors refer to the transport activity of each vehicle fuel combination. All authors have aggregated countries to about 11–13 world regions. Thus, the emission factors are assumed as regional averages and differences between countries within one region are neglected.

More than two thirds of the total global fuel is consumed in OECD countries, most of which in the US. Hence, the much higher data uncertainties in non-OECD regions and eventual corrections applied have not influenced much the global balance. However they will be important for the total exhaust emissions in the respective regions, as the emission level strongly depends on the vehicle technology.

2.1.1. Emissions of road transportation worldwide in the year 2000

Total exhaust emissions by road transportation worldwide are summarised in Table 2. As there is largely agreement on the fuel types and their total amounts, the assumptions about emission factors determine the overall results. They concur for CO_2 and NO_x emissions, but there are large differences for all other compounds. To understand them, and hence to judge on the plausibility of one or the other figure, we need to analyse results and emission factors on the regional level; otherwise all will be dominated by the emissions of the OECD region. Emission factors from Aardenne et al. (2005) are based on estimates for 1995 or 1990 in OECD or non-OECD regions. Fulton and Eads (2004) underscore that their data for non-OECD regions are rough estimates only.

2.1.2. Emissions of road transportation in various world regions in the year 2000

The different world regions contribute in variable amounts to the global exhaust emissions. Usually, North America, Europe and the highly populated Asian region contribute significant amounts. However, vice versa, how well the road transport in the important regions has been modelled determines how reliable the resulting global estimate can be considered. Therefore an analysis of the regional emissions is mandatory and there are also further regional inventory data to compare with, often produced with a much more detailed method (e.g. Amann et al., 2008; Baidya and Borken-Kleefeld, 2009; Cai and Xie, 2007; EEA, 2006; Ohara et al., 2007; Streets et al., 2003; US-EPA, 2005). For the purpose of this review

Table 2
Road transportation's exhaust emissions worldwide in the year 2000.

Ref.	CO_2	SO_2	CO	NMVOC	CH_4	NO_x	PM
	Tg	Tg S	Tg	Tg	Tg	Tg N	Tg
1	4276	1.83	186	33.8	n.a.	8.7	n.a.
2	4282	0.95	110	*20.4*[a]	*0.8*	9.1	1.37, BC: 0.72, OC: 0.31
3	4037	n.a.	272	42.3[b]	n.a.	9	2.7

References: (1) Aardenne et al. (2005), (2) Borken et al. (2007), (3) Fulton and Eads (2004).

[a] Evaporative emissions estimate included.

[b] Total VOC emissions.

we cannot go into the details of each approach, but already the comparison of the final results (Table 3) is revealing.

2.1.3. Carbon dioxide emissions

All inventories concur for carbon dioxide emissions both globally and in the OECD regions. The slightly higher value of Aardenne et al. (2005) for North America cannot be confirmed by national (US-DoT, 2006) or international fuel data (IEA, 2004). The higher values of Borken et al. (2007) for Asia and the Reforming Region are due to their corrections of the fuel data as explained above.

2.1.4. Non-carbon dioxide gaseous emissions

Estimates for nitrogen oxide emissions agree within 30 percent across the different inventories, both globally and in the regions. Emission factors of Borken et al. (2007) for OECD regions are slightly higher: It has recently been found that real world emissions from heavy-duty vehicles in Western Europe are by about 30% higher than the mandatory exhaust emission limit values (Hausberger et al., 2003). For carbon monoxide the emission estimates concur for the relative distribution among regions. However, absolute differences are large: Borken et al. (2007) use the lowest emission factors, the more detailed emission inventories for the US and Western Europe (US-DoT, 2006; US-EPA, 2005) have higher ones, while the emission factors assumed by Fulton and Eads (2004) appear rather high. For sulphur dioxide emissions the lower totals of Borken et al. (2007) reflect the reductions in the fuel sulphur contents since 1995, the base year of Aardenne et al. (2005). The emissions of volatile organic compounds, including evaporative emissions, vary strongly. Values by Aardenne et al. (2005) and Fulton and Eads (2004) appear on the high side, while the values from Borken et al. (2007) are significantly lower and thus much closer to the official emission estimates for the US and Europe, respectively (US-EPA, 2005; EEA, 2006). The global estimate of 20.4 Tg NMVOC for the year 2000 in Table 2 includes 4.6 Tg (23%) of evaporative emissions.

Table 3
Road transportation's exhaust emissions by region in the year 2000.

Ref.	CO_2	SO_2	CO	NMVOC	NO_x	PM
	Tg	TgS	Tg	Tg	TgN	Tg
	OECD					
1	2776	0.51	89	14.8	4.3	–
2	2678	0.165	60	8.35[a]	4.7	0.52
3	2919	–	158.2	21.3	4.6	1.1
	of which North America					
1	1639	0.165	64.1	8	2.3	–
2	1566	0.095	40.8	5.3[a]	2.4	0.18
3	1611[e]	–	97	12.6	2.3	0.54
	of which USA					
9		0.13	68	5.3	2.56	0.23
	of which Western Europe					
1	819	0.135	16.6	4.2	1.4	–
2	800	0.046	12.1	2.2[a]	1.6	0.28
3	869	–	44.4	6.2	1.6	0.41
4	842	0.05	20.8	3.7	1.3	0.20[b]
5		0.05	16.32	2.62	1.5	
8	768	0.05	20.15	2.8 (0.59 evap.)	1.4	0.34[d]
	Developing Asia					
1	589	0.765	37	8.9	1.7	–
2	608	0.265	21	5.8[a]	1.9	0.44
3	591	–	51.2	10.3	1.95	0.76
6	–	0.4	–	–	–	–
7	551	0.38	40	10.5	2.1	0.19[c]
	Reforming/Former Communist Countries					
1	153	0.095	11	1.8	0.46	–
2	247	0.04	9	1.8[a]	0.64	0.11
	Africa, Latin America and Middle East					
1	757	0.46	49	8.3	2.25	–
2	750	0.48	20	4.05[a]	1.9	0.3

References: (1) Aardenne et al. (2005), (2) Borken et al. (2007), (3) Fulton and Eads (2004), (4) EEA (2006), (5) IIASA (2001): RAINS-ASIA, (6) Ohara et al. (2007), (7) IIASA (2007): GAINS Europe, C&E CL, NEC6 scenarios (retrieved 07/09/2009), (8) US-EPA (2005).
–: No data.
[a] Evaporative emissions estimate included.
[b] From diesel fuelled vehicles only.
[c] Derived from fuel consumption.
[d] PM_{10} ($PM_{2.5}$: 0.28 Tg).
[e] About 1514 Tg CO_2 without MEX, that accounts for about 6% of the total road fuel consumption in NAM + MEX.

Table 4
Total and road transportation emissions for BC, POM and SO_2.

	BC [Tg yr^{-1}]	POM [Tg yr^{-1}]	SO_2 [TgS yr^{-1}]
Emission total for reference year 1996	8.0 (Bond et al., 2004)	33 (Bond et al., 2004)	74.8 (Boucher et al., 2002)
Emission from road transportation for reference year 2000	0.72	0.31	0.95
Fraction (%) of emissions	9.0	0.9	1.3

2.1.5. Emissions of particulate matter

For PM emissions the large differences can be traced back to the emission factors assumed for gasoline vehicles. Emissions factors broadly concur for diesel vehicles between Borken et al. (2007) and Fulton and Eads (2004). However for gasoline-powered vehicles Fulton and Eads (2004) assume as much as 40–50% of the respective value of diesel vehicles without giving a reference. Usually PM emissions of gasoline-powered vehicles are about two orders of magnitude smaller (Bond et al., 2004; US-EPA, 2003; Samaras et al., 2005). According to *Quantify* calculations about 9% of the total black carbon emitted is attributable to road transportation, from which 98.7% of the BC produced comes from diesel from road and freight traffic whereas only the remaining, 1.3%, comes from gasoline. Fig. 3 illustrates the area with maximum BC atmospheric content which are contributing to the overall aerosol burden: Western Europe, Asia in particular over India and Eastern Asia, Northeastern United States.

Aging, mixing and changes in properties make it difficult to attribute atmospheric aerosol to certain sources. For example, 20% of the black carbon is considered as soluble whereas 80% is treated as insoluble upon emission. As the aerosol ages, the insoluble BC becomes soluble with an e-folding lifetime of 1.1 day. For organic carbon the soluble fraction even amounts to 50% upon emission. Exchange processes with water droplets and aerosols from other sources take place.

Usually, inventories calculate mass emissions of primary PM_{10}, though health evidence suggest that mass or number concentrations of fine and ultrafine particles ($PM_{2.5}$, PM_1 and finer) are more relevant (cf. chapter 3.3). However, reliable emission factors for these particle fractions are not yet available for the different vehicle technologies and world regions. As an indication, Bond et al. (2004) assume that more than 85% of all exhaust PM emitted from road vehicles belongs to the PM_1 fraction. Size resolved measurement data reveal that about 90% of these particles have an aerodynamic diameter below 0.5 μm (e.g. Birmili et al., 2009; Ketzel et al., 2004, 2007; Rose et al., 2006; Samaras et al., 2005) and hence are in the health relevant size segment.

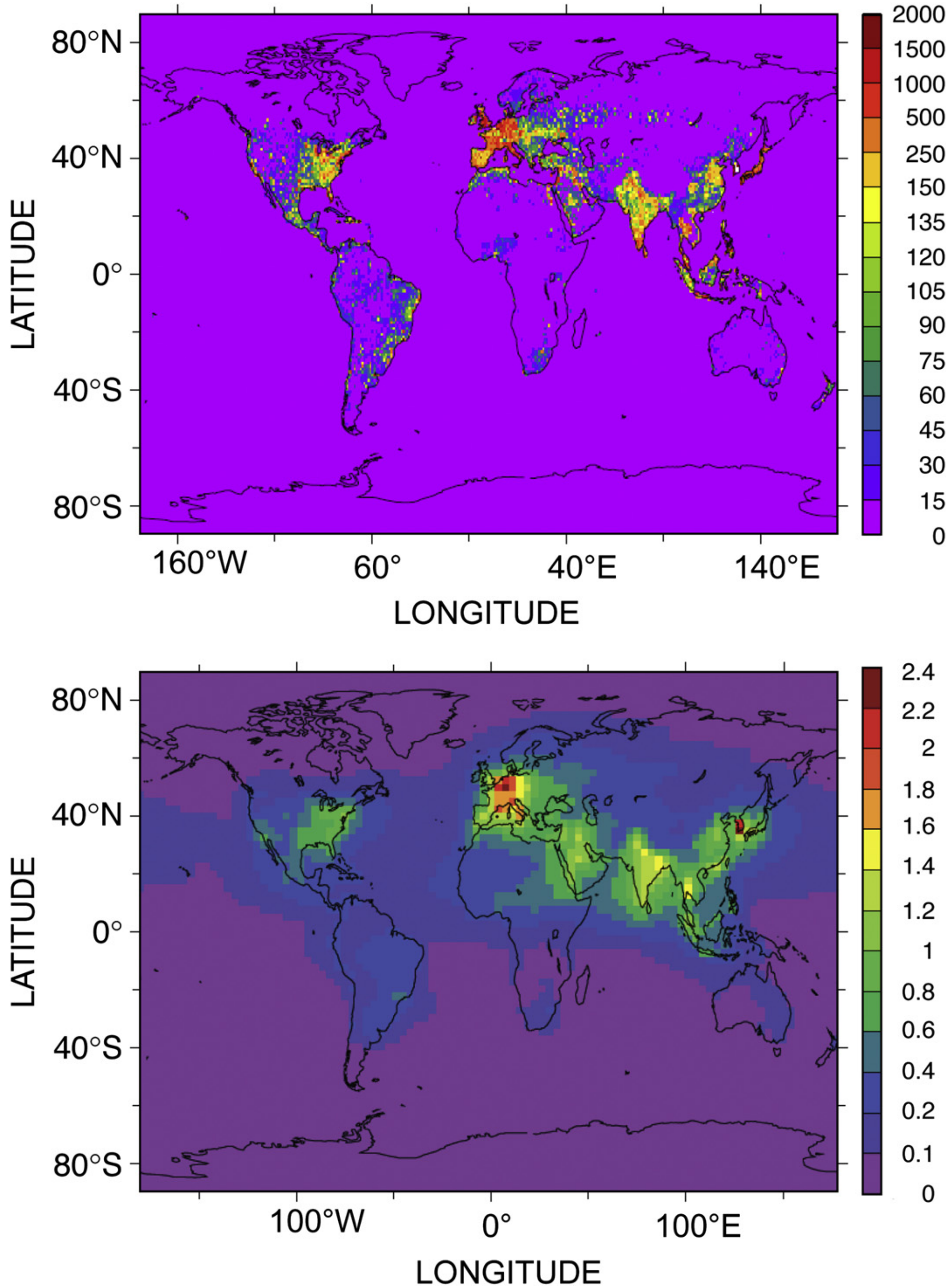

Fig. 3. Top panel: Total amount of black carbon (tonnes carbon yr^{-1}) emitted from passenger and freight transport (Gasoline + Diesel), Borken et al. (2007). Bottom Panel: black carbon optical depth ($\times$1000) from passenger and freight transport (gasoline + diesel) global mean, ecmwf winds for 2000.

Vehicle emissions of air pollutants strongly depend on the exhaust emission control devices and their operation efficiency in a given year. This needs a careful characterisation of the technical characteristics of the fleet in a given year. Therefore, a large part of the differences in the three global emission estimates reviewed here (Aardenne et al., 2005; Borken et al., 2007; Fulton and Eads, 2004) can be traced back to differences in technologies assumed. For instance, Aardenne et al. (2005) are bound to have high emission estimates as they use emission factors average for 1995 technologies. These do not capture the important tightening of emission controls in many industrialised countries.

2.1.6. Uncertainties

The biggest differences in values are for the region of developing Asia, comprising China, India and the growing South East Asian economies. This region has undergone a very rapid development in road transport volume and increase in vehicle stock. Therefore the state for the year 2000 is difficult to estimate. Furthermore, vehicle

Table 5
Estimate of the uncertainty for road transport emission in the year 2000 (Borken et al., 2007).

	CO_2	SO_2	CO	NMVOC	NO_x	PM
OECD						
Emission share	61%	16%	52%	40%	49%	36%
Uncertainty	5%	13%	30%	30%	30%	50%
non-OECD						
Emission share	39%	84%	48%	60%	51%	64%
Uncertainty	20%	30%	60%	60%	40%	75%
Cumulated uncertainty	11%	27%	44%	48%	35%	66%

exhaust emission control has not been as stringent as in OECD countries and hence their variability is bigger.

Moreover, the inventories differ in the sophistication of the approach and in the quality of their input data. Therefore the range of values rather reflects the outcome of various more or less well controlled simplifications not the range of uncertainty.

To estimate the potential uncertainty we give the following expert judgement for the year 2000 based on the differentiated results of Borken et al. (2007): The input data (vehicle stock composition and their mileage, the emission factors and the overall fuel balance) are more reliable and less variable in OECD countries. Our judgement goes for 5% uncertainty in the fuel balance and related CO_2 emissions over an estimated 30% uncertainty for CO, NMVOC and NO_x to about 50% uncertainty for PM emissions. For non-OECD countries the available data are much less representative, less reliable and the variation in vehicle technology and operating conditions is much larger. Consequently we have assumed about a two to three times higher uncertainty for each species. Weighted with the respective region's share in emission we estimated a cumulated uncertainty in the order of 10% for CO_2 emissions, about 30% for SO_2 and NO_x emissions, 40–50% for CO and NMVOC emissions and 66% for PM (Table 5).

2.2. Emissions of rail transport

In many countries railway plays an important role in transport of goods and passengers. Globally rail transport's performance is 2.2 (±0.4) trillion passenger km and 8.6 (±1.7) trillion tonne km per year. Approximately one third of this transport takes place in Europe. Rail goods transport plays an important role in North America while ¼ of the global rail passenger transport takes place in India and China, respectively (Community of European Railway and Infrastructure Companies). In EU-25 rail contributes to 9% of total passenger transport and 3% of the goods transport (EEA, 2006). Approximately 30% of the global rail network is currently electrified; this share is 50% in the European Union.

Table 7
Rail emission factors.

	NO_x	CO	NMVOC	$PM_{2.5}$	CH_4	N_2O
IPCC (kg TJ^{-1})	1200 (300)	1000 (150)	100 (20)	–	5 (10)	0.6 (1.4)
EMEP/Corinair (kg TJ^{-1})	915	247	107	112	4	29

() = coal.

The remaining railway network is using fossil fuels, namely diesel oil for propulsion. Due to large coal resources of the country coal driven trains are still common in China (IEA).

2.2.1. Fuel consumption and carbon dioxide emissions

There is yet no global gridded rail inventory available. The global EDGAR inventory includes railways, but together with inland waterways and pipeline transport. EMEP prepares a gridded rail inventory for Europe based on data reported by the Parties to the Convention, which is however not fully complete (http://www.emep.int/index_data.html).

European (EU-25) rail emissions have also been estimated by the EEA TERM (2003). This study shows that rail emissions in Europe make up for only 1–3% of the total transport emissions.

Rail fuel consumption data are available for all world regions at the country level from the IEA for all years since 1971. Selected years are presented in Table 6. The table shows a large decline in coal consumption, a 70% increase in electricity consumption and stable diesel consumption from 1971 to 2004.

The energy consumption can be used to estimate global carbon dioxide emissions. We address only direct emissions here excluding electricity generation and other indirect emissions which are discussed in Section 2.4. Information about rail emission factors as also shown in Table 7 can be found in the EMEP/Corinair emission inventory guidebook EMEP/CORINAIR (2006), the IPCC (1995) inventory Guidelines and UIC/CER (2006).

2.2.2. Emissions of short-lived pollutants

European rail vehicles produced after 1990 emit substantially less NO_x and PM compared to older vehicles. For example for mainline locomotives the reduction has been 30% in NO_x and 70% in PM emission factors, while for railcars the reduction has been even larger (UIC/CER, 2006). We have estimated emissions using the EMEP/Corinair emission factors for diesel and the IPCC emission factors for coal. The UIC/CER emission factors are only applicable for Europe. The uncertainty margins are large for all emission data given the uncertainty in emission factors and fuel consumption and the fact that independent studies are not available for verification.

The estimates shown in Table 8 illustrate that rail emission are small compared to the emissions from road transport. Nevertheless, the mode is important as part of a transport inventory and

Table 6
Energy consumption in railways for selected years and per world region. Coal and diesel (kt) and electricity (GWh). (n.a. = no data available).

	1971			1980			1990			2004		
	Coal	Diesel	Electricity	Coal	Diesel	Electricity	Coal	Diesel	Electricity	Coal	Diesel	Electricity
World	–	28,102	107,346	48,738	35,166	154,490	35,432	34,152	182,253	8328	33,076	184,950
EU-25	–	n.a.	n.a.	n.a.	n.a.	n.a.	181	3877	48,089	1	2518	58,403
Non-OECD Europe	–	n.a.	567	20	n.a.	1936	14	103	2207	n.a.	308	2136
Africa	–	187	2771	2217	299	4446	280	217	4370	7	343	3911
Latin America	–	378	1126	80	612	1224	2	560	2015	1	596	2119
Asia Excl. China	–	622	1663	11,950	979	2514	5265	1832	4700	n.a.	2907	12,622
China	–	n.a.	n.a.	19,344	n.a.	2650	20,271	2047	5936	8194	7833	20,016
Former USSR	–	8200	48,800	12,007	11,300	76,000	9423	11,600	87,000	125	4721	50,674
Middle East	–	8	n.a.	n.a.	10	n.a.	n.a.	17	n.a.	n.a.	n.a.	n.a.

Table 8
Emissions from rail (n.a. = no data available).

	CO_2 [Tg yr^{-1}]				NO_x [GgN yr^{-1}]			
	1980	1990	2000	2004	1980	1990	2000	2004
World	209.0	179.1	119.7	121.5	512.8	476.3	393.7	413.9
EU-25	n.a.	12.7	9.3	8.0	n.a.	47.1	35.5	30.3
Non-OECD Europe	n.a.	0.4	1.3	1.0	0	1.3	4.9	3.7
Africa	5.4	1.2	1.2	1.1	7.6	3.1	4.5	4.1
Latin America	2.1	1.8	1.4	1.9	7.5	6.8	5.3	7.2
Asia excluding China	27.0	16.3	6.1	9.2	33.6	31.7	23.1	35
China	38.7	47.0	44.5	41.2	35.3	61.7	108.2	109.4
Former USSR	59.8	55.6	13.7	15.2	158.1	157	52	57.1
Middle East	n.a.	0.1	n.a.	n.a.	0.1	0.2	n.a.	n.a.

assessment due to rails important role in current, and expected future transport policies. From a climate perspective rail transport will compared to air and road transportation imply less emissions per passengers and freight transported (EEA TERM, 2003), since per passenger emissions from road transport are more than twice as high as those from rail, while emissions from air transport are 10–20% higher than those from road (average figures for EU-15). For freight, on a tonne km basis, emissions from road are around five times as high as those from rail while they are more than 8 times as high as emissions from maritime shipping. These figures however mask differences in average distance travelled and capacity utilisation (EIONET, TRENDS, 2003).

2.3. Emissions of inland shipping

Inland shipping, defined as shipping on rivers and lakes, is not important in terms of emissions at the global level, but can play an important role for transport primarily of goods at the local level. Emission estimates are not always comparable in different studies, since the differentiation between ocean going ships and inland shipping is not always sharp. But emissions from shipping on inland waterways are below 1% of all emissions from transport. For the EU 27 region the IIASA Gains model (IIASA, 2007) reports CO_2 emissions of 5.73 Tg for 2000 and 7.41 Tg for 2005. This is 0.7% or 0.85% of the emissions from cars, trucks and buses. In Europe (EEA 30) inland shipping is estimated to have a share of 5% in freight transport (EEA Report No 1/2007), but there is no relevant passenger transport. Inland shipping will not affect the global climate to a measurable extent.

2.4. Indirect emissions

Transport generates direct emissions when fuel is combusted in the engine of the vehicle. However, when assessing the land transport impact on climate it is evidently relevant to consider all emissions generated as a result of transport activities. The use of transport infrastructure like roads, rail-lines and harbour facilities but also bridges, car parks, tunnels or filling stations requires energy for construction work, maintenance and production of materials (e.g. asphalt, concrete and steel). Production of the vehicles requires energy, in particular for primary products (e.g. steel, aluminium and plastic). Besides from these material related emissions, production of fuels generates emissions from extraction, refining and transportation which will be discussed as well-to-tank emissions.

2.4.1. Material related emissions

Although construction and maintenance of transport infrastructure are usually attributed to other emission sectors (mainly industry or construction) and adding them also to the transport emissions would mean a double counting, we need to be aware that many of these emissions grow with the respective transport mode. In particular for road and rail transport they are not negligible compared to the tailpipe emissions.

Chester and Horvath (2009) find in a total life-cycle assessment of transport modes in the United States, that considering infrastructure, fuel production and supply chains leads to greenhouse gas emissions, which are 1.4–1.6 times higher for onroad transport and 1.8–2.5 times higher for rail transport than emissions from the tailpipe only. 7–8% of the total life-cycle's GHG emissions are attributed to vehicle manufacturing, 3–5% to vehicle maintenance. This corresponds to about 12% and 6% of the tailpipe emissions. The Japanese institute for Lifecycle Environmental assessment (http://www.ilea.org) estimates similar emissions from production of a gasoline conventional vehicle of about 1/8(12–13%) of the total CO_2 emissions from tailpipe. Samaras and Meisterling (2008) attribute for a Toyota Corolla type vehicle 35 g CO_2-eq km^{-1} to the car manufacturing, 177 g CO_2-eq km^{-1} to the gasoline consumption on site and 57 g CO_2-eq km^{-1} for gasoline upstream emissions (e.g. distribution and refining). Thus, production related emissions are 15% of the gasoline related emissions and 20% of the tailpipe emissions. In this study 102 GJ or primary energy demand (8.5 tonnes of CO_2-eq) are estimated for the production and the car life is assumed to be 240,000 km. Schmid (2003) estimated twice as much, 69 g CO_2-eq km^{-1}, for the total of manufacturing, maintenance and end-of-life emissions. This corresponds to Jancovici (2004), who reports that about 15% of the CO_2 emissions can be attributed to the production and another 15% to the maintenance (Jancovici, 2004). Although values vary depending on the assumptions made a common range of 12–20% emissions for manufacturing compared to tailpipe emissions is assumed for conventional vehicles. In comparison, a life-cycle analysis for a ferry concluded that 97% of CO_2 emissions are from operation, 1.4% from construction, 0.65% from maintenance and 1.1% from scrapping (Johnsen and Fet, 1999).

For construction, maintenance and end-of-life of a train with 3 wagons of 100 seats each and 30% occupancy emissions of about 8 g CO_2-eq per passenger kilometre travelled (PKT) can be deduced from data of Schmid (2003) for a German train. This is similar to values of about 11 g CO_2-eq per PKT (or 30% of vehicle operation) estimated by Chester and Horvath (2009) for CALTRAIN in California. A higher share of emissions, about 65% of those from vehicle operation, are estimated for rail's infrastructure construction and operation (Fig. 4).

Chester and Horvath (2009) allocate 9–13% of the life-cycle emissions (about 20% of the tailpipe emissions) to infrastructure construction. 200 tonnes of CO_2-eq (2500 GJ energy) are estimated to be emitted during the construction of 1 km lane of an average US road. Such estimations have high uncertainties. For example, another study on an Australian continuously reinforced concrete road calculated nearly four times higher energy needs and emissions (Treloar et al., 2004; pers. comm. Robert Crawford).

2.4.2. Well-to-tank emissions

Well-to-tank emissions are relevant for all fuels used for transport and include emissions from extraction, processing and refining as well as evaporative emissions from fuel distribution. Combustion emissions from transportation of the fuels are already included in the datasets in Sections 2.1–2.3.

The indirect emissions are at present most important for electricity production (power plants) for use in railways and to a small extent for road transport. Indirect emissions from electricity provision will depend on the technology used for producing the electricity and abatement level. Due to increasing electrification of the railway network, indirect CO_2 emissions for rail are nowadays

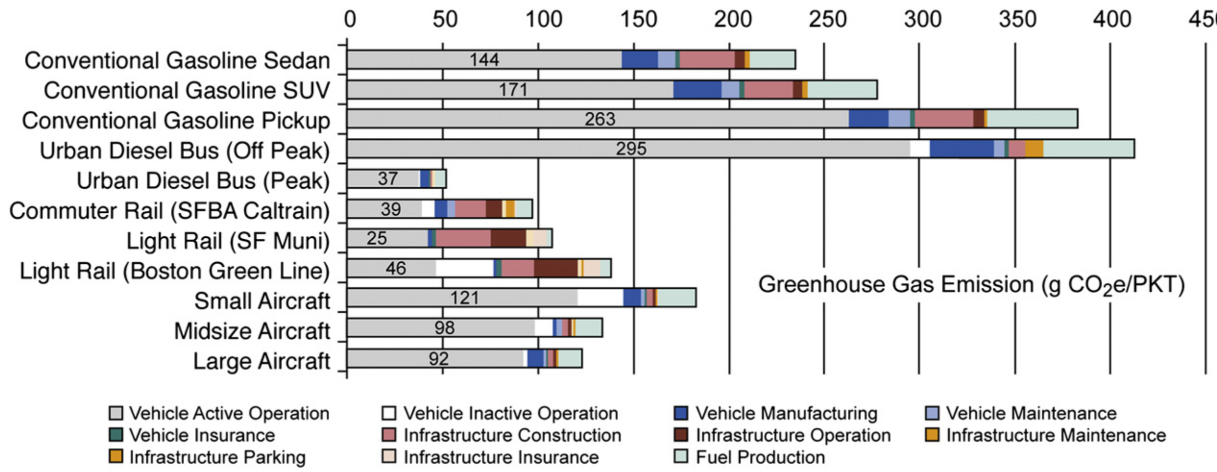

Fig. 4. GHG emissions per PKT for different vehicle types from Chester and Horvath (2009). The vehicle operation components are shown with gray patterns. Other vehicle components are shown in shades of blue. Infrastructure components are shown in shades of red and orange. The fuel production component is shown in green.

approaching the same order of magnitude as direct emissions. It is important to include this component in an assessment of future emission where more of the transport system is being electrified, in rail and also in road transport. A life-cycle assessment of greenhouse gas emissions demonstrated for the present electricity mix in the United States that plug-in hybrid electric car are hardly beneficial compared to normal hybrids (Samaras and Meisterling, 2008). Future emissions per unit of electricity produced are, however, also expected to change. For example, use of carbon capture and storage and more use of solar and wind power will reduce emissions substantially. For such a low-carbon scenario life-cycle GHG reductions could be 51–63% for plug-in hybrids compared to conventional vehicles.

Also fossil fuels have a footprint from the extraction phase and refineries. Energy requirements for extraction and processing/refining generate i.e. CO_2, NO_x and SO_2 emissions. Due to low sulphur content in fuel, the total SO_2 emissions from all indirect sources are estimated for the US to be 19–26 times larger than the operational emissions (Chester and Horvath, 2009). In addition there are fugitive emissions of methane and NMVOCs from the extraction, refining and transport of fuels. Typically CO_2-equivalent emissions of direct greenhouse gases well-to-tank would constitute 14 and 16 percent of well-to-wheel emissions for conventional gasoline and diesel road vehicles, respectively (JRC/CONCAWE/EUCAR, 2006). Chester and Horvath (2009) estimate a similar average ratio of 13–15% fuel production related emissions compared to operational emissions for the US passenger car fleet.

Gasoline used for road transport is a light and relatively volatile fuel. Therefore it is more easily evaporated during handling and use compared to diesel fuels and heavy fuel oil. Gasoline distribution and tanking is an important NMVOC source, depending on fuel properties, climate and technologies. In Europe tighter standards for emissions from gasoline stations have resulted in reduced emissions the last years. In addition to exhaust emissions, gasoline vehicles themselves will result in evaporative emissions (EMEP/CORINAIR, 2006). These emissions can be classified as running losses, hot soak and diurnal (daily) emissions (ibid). Diurnal emissions are associated with daily variations in ambient temperature that results in vapour expansion inside the gasoline tank and contraction during nights with lower temperature. Hot soak emissions occur when a hot engine is turned off and heat from the engine and the exhaust system increases the temperature of the fuel in the system. Running losses are the result of vapour generated in gasoline tanks during vehicle operations. Modern vehicles control these emissions by 90% (EMEP/Corinair, 2006) compared to older vehicles. Some quantitative estimations are given in Section 2.1.

In recent years and likely in the near future biofuels are increasing in importance for use in road transportation and perhaps also in shipping. Emissions from the production of biofuels must be added to the indirect emissions. This will include emissions from fertilization and fertilizer production (N_2O and CO_2), fuel processing, transport of fuels and even CO_2 emissions from land use change. Synthetic fuels, for example hydrogen, will shift most emissions to the production stage. An overview of these well-to-tank emissions from alternative fuels is given in the well-to-wheel analysis as described in Section 5.3 (cf. JRC/CONCAWE/EUCAR (2005, 2003 and online: http://ies.jrc.ec.europa.eu/wtw.html 2006)).

2.5. CFC and HFC emissions

Emissions from transport include emissions from mobile air conditioners (MAC) in passenger vehicles or cooling/freezing systems of goods transport. We do not discuss emissions from the latter in this report. Air conditioning in cars became common in the United States since 1960. However, mass production in Europe and in the developing countries started later, in about 1995. In 2000 half of the worldwide automotive fleet of 720 million vehicles was equipped with air conditioners (SROC, 2006). This number is increasing. Previously CFC-12 (CCl_2F_2) was used as chemical in MAC, but in 2003 HFC-134a (CH_2FCF_3) was already used in 338 million road vehicles. In the near future they are envisioned to be replaced by CO_2 or HFC-152a (difluoroethan, CHF_2CH_3). The emissions of HFC-134a take place during accidents, through leakage and servicing and at disposal. The recovery rates are low. A US model study estimates the loss by leakage and service to be 10.9% and the loss during disposal to be 42.5% of the total MAC charge in developed countries and 69% in developing countries (DeAngelo et al., 2006).

Indirect emissions arise from additional fuel use of the vehicle in which the MAC is installed. This can amount to 2.5–7.5% of the total fuel consumption, depending on the operation time. These emissions depend strongly on the local climate and can only be roughly estimated. Systematic inventories for additional fuel consumption are not yet established. But the resulting CO_2 emissions are included in the emission figures in Sections 2.1–2.3.

In 2002 about 110–130 ktonnes of CFC-12 were emitted. This is slightly more than a quarter of the 1990 emissions (400–430 ktonnes). Half of the 2002 CFC-12 emissions were emitted from MAC. 63 ktonnes are estimated for 2003 (SROC, 2006).

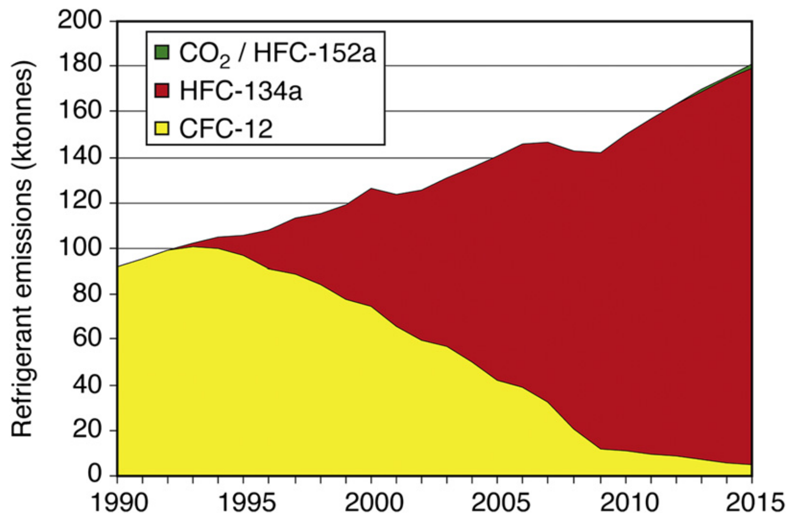

Fig. 5. SROC (2006), Fig. 6a. MAC refrigerant emissions from 1990 to 2015 (Clodic and Palandre, 2004).

A typical air conditioner in a car contains 1 kg of CFC-12 or 0.8 kg of HFC-134a (Atkinson, 2000). Fig. 5 shows that the total amount of refrigerants emitted is constantly rising, but now mainly consisting of HFC-134a. In 2002, about two thirds of the 97 ktonnes emitted came from MAC. As can be seen from estimations that were made in 1999 (Fig. 6), much faster progress in the market integration of CO_2 or HFC-152a based systems was assumed before. But alternatives to HFC-134a needed longer development and test phases (SAE, 2003). Furthermore, the strong increase in the market share of cars equipped with air conditions of up to more than half of the fleet at present was not expected. Consequently, recent estimates for MAC refrigerant emissions in 2005, suggesting 140 ktonnes, are more than twice as high as projected in 1999. We can see that as one example how difficult it is to project future developments if the introduction of new technologies is planned.

The introduction of HFC-134a led to a sudden and strong increase of this compound in the atmosphere, reaching mixing ratios of 25.5–30.6 ppt within the ten years after 1995. However, the atmospheric relevance of HFCs is clearly different from CFCs and will be discussed in Section 4.2.

3. Impacts on air composition

3.1. Basics of atmospheric chemistry

For atmospheric chemistry, the main concern related to land transport derives from emissions of nitrogen oxides (mainly $NO_x = NO + NO_2$), non-methane hydrocarbons (NMVOC) and carbon monoxide (CO), which are precursors of ozone and thus affect the oxidizing capacity of the atmosphere. Through their impact on OH they also affect methane, constituting a secondary, longer-lived effect on climate. In contrast to the impact from shipping and aviation, there have been only few publications focusing on global chemical and climate effects of road emissions (e.g. Granier and Brasseur, 2003; Grewe, 2004; Niemeier et al., 2006; Matthes et al., 2007). The main chemical mechanisms of relevance to road emission assessments are summarised in the following paragraphs.

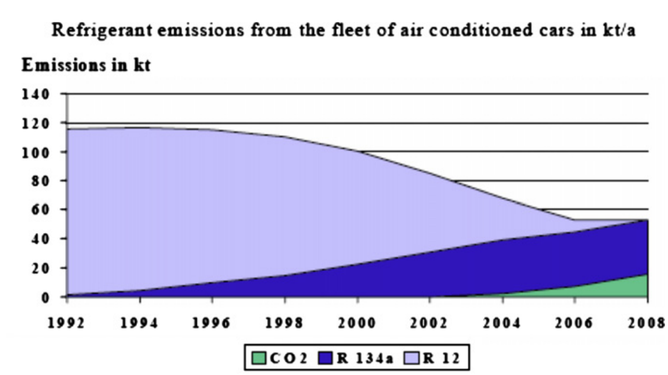

Fig. 6. Refrigerant emissions from the fleet of air conditioned car in kt/yr as estimated in 1999. Source: Preisegger E., Solvay Fluor und Derivate GmbH.

Ozone production in the troposphere proceeds in the presence of NO_x and sunlight via

$$NO_2 + h\nu \rightarrow NO + O \quad \text{R1}$$

$$O + O_2 + M \rightarrow O_3 + M \quad \text{R2}$$

$$NO + HO_2 \rightarrow NO_2 + OH \quad \text{R3}$$

The HO_2 radical that reconverts NO into NO_2 (reaction (R3)), can be produced from the oxidation of carbon monoxide or hydrocarbons, e.g.

$$CO + OH \rightarrow CO_2 + H \quad \text{R4}$$

$$H + O_2 + M \rightarrow HO_2 + M \quad \text{R5}$$

with similar reactions involving methane and other hydrocarbons. NO_x has a rather short chemical lifetime and its largest effects on ozone are confined to the vicinity of the emission sources. From ozone, the OH radical is formed in the presence of water vapour and sunlight (Fig. 7):

$$O_3 + h\nu \rightarrow O^* + O_2 \quad \text{R6}$$

$$O^* + H_2O \rightarrow OH + OH \quad \text{R7}$$

OH is the main oxidizing agent in the atmosphere, reducing the concentration of CO and CH_4 but also of most other gaseous pollutants. OH can be enhanced by road transport not only due to the ozone enhancement but also directly due to NO_x emissions that move the HO_2/OH balance towards OH. Since CO and CH_4

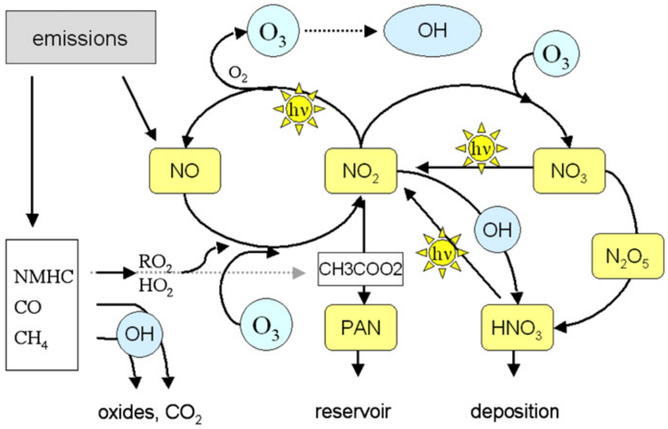

Fig. 7. Basic processes in tropospheric chemistry.

have lifetimes of about 2 months and 8 years, respectively, they constitute a longer-lived effect of road-traffic emissions and can transport the signal over large distances. Enhanced CO and CH_4 levels in turn can reduce OH in remote unpolluted areas. As stated in Niemeier et al. (2006) the sign in the OH perturbation by road traffic is determined by the ratio between the intensities of NO_x and CO perturbations. NO_x perturbations enhance OH, while CO emissions reduce it. The absolute changes in the zonally averaged OH concentration resulting from the extensive use of automobiles are thus relatively limited (Granier and Brasseur, 2003).

NO_x as such cannot be transported over large distances due to its short lifetime. However, Matthes et al. (2007) found that the formation of relatively long-lived PAN species (peroxyacetyl nitrates) from NMVOC and NO_x has the potential to transport the signal of road traffic to remote areas such as the Arctic. PAN is decomposed in areas of subsidence, releasing NO_x and thus effectively enhancing ozone in remote unpolluted areas. This makes emissions of NMVOC from road traffic important even for remote regions. The ozone production efficiency per emitted NO_x molecule decreases at higher NO_x levels. At very high NO_x concentrations ozone titration becomes important:

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad \text{R8}$$

which can lead to a local reduction of ozone in high NO emission areas. However, further downwind from road traffic or in case of direct NO_2 emission from vehicles with particle filters ozone is increased. Due to the dependence of reaction (R1) on sunlight the ozone production from road traffic is much larger during summer, while in winter ozone net reductions can occur through ozone titration by the emitted NO.

Nitrogen deposition and acid rain are enhanced through road-traffic emissions of NO_x, CO and sulphur components. E.g. NO_x from road traffic is converted into nitric acid, which is highly water soluble and washed out, leading to nitrogen deposition.

$$NO_2 + OH \rightarrow HNO_3 \qquad \text{R9}$$

This reaction can counteract the OH enhancement due to NO_x emissions from road traffic, especially under low-sunlight conditions. According to Granier and Brasseur (2003) surface OH decreases substantially in January in response to automobiles and trucks emissions in the highly polluted regions of Europe and North America where the background nitrogen oxide level is so high that additional NO_x tends to convert substantial quantities of HO_x into nitric acid.

Other minor effects of road-traffic emissions exist with respect to heterogeneous chemistry through emissions of particles and to stratospheric ozone depletion through the slowly expiring emission of CFCs from MAC in vehicles. Long-lived CFCs are transported into the stratosphere where they are decomposed by sunlight into inorganic chlorine, in part present as Cl and ClO radicals that cause catalytic ozone depletion through

$$Cl + O_3 \rightarrow ClO + O_2 \qquad \text{R10}$$

$$ClO + O \rightarrow Cl + O_2 \qquad \text{R11}$$

Most of the stratospheric inorganic chlorine is present as so-called reservoir species, HCl (hydrochloric acid) and $ClONO_2$ (chlorine nitrate), which themselves do not destroy ozone. However, heterogeneous processes, e.g. on Polar Stratospheric Clouds, which are present under very cold conditions in the Arctic and Antarctic stratospheres, convert the reservoir species back into less stable components that during spring are readily decomposed into Cl and ClO by sunlight, leading to severe ozone depletion. Current research in regard to chlorine chemistry has concentrated on the role of the ClO dimer (ClOOCl) which, according to a recent publication of Pope et al. (2007), appears to be more stable than previously suggested, thus implying a smaller role of chlorine for stratospheric ozone depletion as less ClO radicals are released.

HFC-134a, which has replaced CFC-12 in new MAC, has a much shorter lifetime ($\sim$14 years) because it reacts with OH in the troposphere. Its effects in the stratosphere are thus much less pronounced.

3.2. Impacts on global atmospheric composition and chemistry

3.2.1. Key species and model approach

Emissions of long-lived species like CO_2, methane and halocarbons as well as short- lived compounds like carbon monoxide, nitrogen oxides and non-methane volatile organic compounds (NMVOC) both can lead to changes in the global atmospheric composition. Here, we focus on chemical impacts of short or medium lived gases. As we saw, their emission influences the formation of secondary pollutants and oxidants like ozone, the hydroxyl radical (OH), the NO_x reservoir species PAN and methane. Radiative forcing impacts are discussed in Section 4.

Carbon monoxide and methane are both removed from the atmosphere by OH and have a relatively long tropospheric lifetime of a few weeks up to two months and about 8 years, respectively. The background of the OH depleting carbon monoxide is enhanced by many fossil fuel related and biomass burning sources. Therefore, CO emissions from land transport are less significant, on a global scale although not negligible and clearly higher than for other transport sectors. Transport emissions of NO_x and NMVOC have a substantial influence on O_3 and OH, and also on methane lifetime through the reactions described in 3.1.

Table 9
Global transport and non-transport emissions in the year 2000 as used in Hoor et al. (2009).

	NO_x		CO	
	TgN yr^{-1}	%	Tg yr^{-1}	%
Road (preliminary)	6.85	14.7	73	7.4
Ship	4.39	9.4	1.4	0.1
Air	0.67	1.4	0	0
Non-traffic	27.8	59.7	796	81
Biogenic	6.89	14.8	113	11.4
Total	46.6	100	983	100

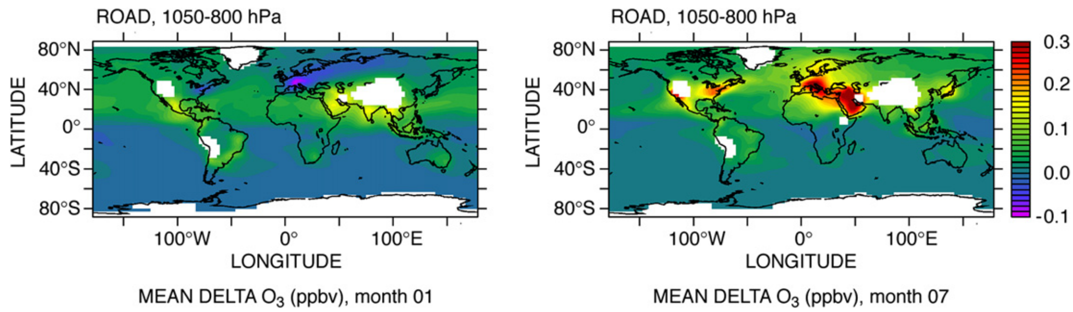

Fig. 8. Mean perturbations of ozone (ppbv) in the lower troposphere (surface − 800 hPa) during January (left) and July (right) applying a 5% emission reduction (Hoor et al., 2009).

Since impacts of land transport add to or interact with impacts from other sources, they cannot be directly measured in the real world but have to be estimated from models. Only few calculations have been carried out so far (Niemeier et al., 2006; Matthes et al., 2007), the most recent in the EC-*Quantify* project (Hoor et al., 2009). We discuss *Quantify* results being aware that they are not based on the most recent emission datasets presented in Section 2, but on an older dataset shown in Table 9.

Calculations using more recent emission data are not available and a linear extrapolation might cause misleading results because of interdependencies described in Hoor et al. (2009). However, in general the impacts described below will be stronger for the emissions presented in Section 2 of this article.

In order to estimate the impacts of transport emissions against the background of all natural and anthropogenic emissions, "base case" model runs have been carried out including all emissions. The base case is compared with a "perturbed case" model run in which the transport emissions are reduced by 5% (Hoor et al., 2009). This approach was chosen and preferred to a direct 100% reduction of the transport emissions to allow to add up the effects of each transportation mode and to avoid non-linear responses of the chemical system due to interactions with different chemical background conditions at different locations. Such interactions are switched off in a 100% reduction approach as applied in an earlier study (Matthes, 2003). In the *Quantify* calculations shown here all transport sectors were included. The used draft emission inventory of Borken-Kleefeld is described in detail in Hoor et al. (2009). Uncertainty ranges as discussed in Section 2.1 of this report are on average about 30–40% for NO_x emissions and 30–60% for carbon monoxide (this publication, Table 5; Matthes, 2003).

3.2.2. Impacts on ozone

The impact of transport emissions on global ozone is presented in Fig. 8 measured as the difference in the concentrations between the base case and the perturbed case.

Based on the 5% perturbation of road-traffic emissions highest sensitivities in the northern hemisphere can be up to 0.18 DU in summer and 0.07 DU in winter. If a linear scaling of this modelling results to 100% would be applicable (this is questionable because of the non-linearity of the chemistry) this would mean for the total road traffic contribution up to 3.5 Dobson Units (DU) in summer and up to 1.4 DU in winter. The results are of a similar magnitude compared to respective values of 5.2 DU and 2.1 DU found by Matthes (2003) based on emission data from 1990 with higher NO_x. Changes in the Southern Hemisphere are weak and, probably due to interhemispheric transport, in phase with the Northern Hemisphere. On a global average land transport contributes relatively strongest to the total ozone column in the NH summer in industrialised regions with dense transport (Eastern US, Europe, Near East, Japan). The strongest impact is seen in regions where at least two relevant factors come together: a large car fleet, limited control of air pollution, dry and sunny weather conditions. Such regions are Italy, Eastern Europe and the Near East. This is because ozone formation depends on photolysis and the OH concentration. Both are higher in the NH summer. The chemistry of hydrocarbons has in many cases an additive influence (Matthes, 2003). In the dark winter months, however, the contribution of land transport to ozone formation is minor or can even be slightly negative on a regional scale, for example over Europe. The deviation between different models is in the range of 15–30% for the most affected regions.

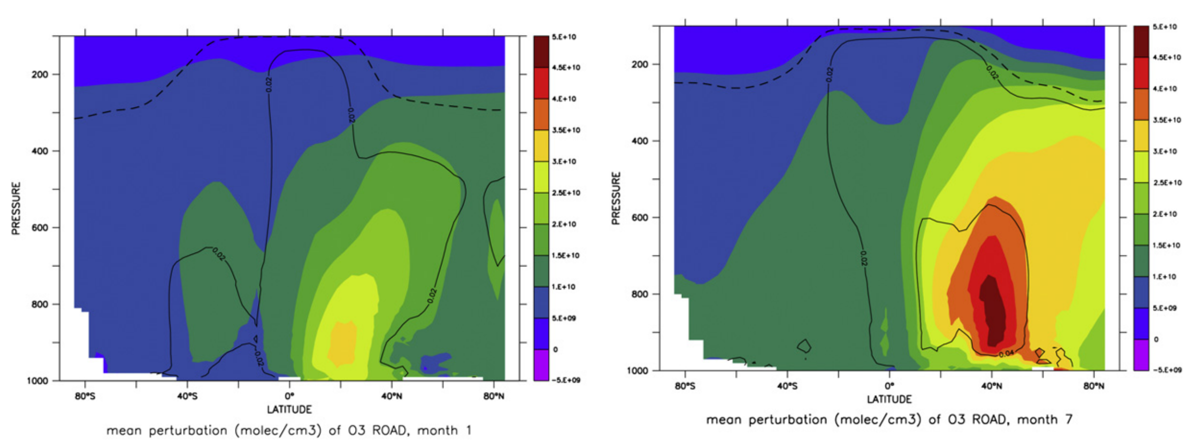

Fig. 9. Zonal mean contribution of road traffic to ozone in molecules per cm^3 in January (left) and July (right), average from four models. Isolines of 2% and 4% change and the tropopause (dashed line) are shown in the graphs. Source: Hoor et al. *Quantify*.

A remarkable result of the models shown in Fig. 9 is that the impacts of road traffic extend from the boundary layer to the free troposphere and even to the Upper Troposphere–Lower Stratosphere (UTLS) region. Although in the UTLS region (250 hPa layer, 11 km altitude) aircraft emissions dominate the traffic impact, road emissions can reach a similar magnitude in summer. Ship emission impacts, in contrast, are more strongly confined to the planetary boundary layer (PBL) because of less vigorous convection, which is much stronger over land, especially during summer. Ozone is transported from the source regions to the free troposphere and UTLS region where its contribution to climate change is strongest. Therefore, it is more meaningful for the illustration of the climate effect to show the total tropospheric ozone column rather than ozone changes in the PBL.

The relative contribution of road-traffic emissions to atmospheric ozone, again if linearly scaled from a 5% perturbation, reaches about 2–6% zonally averaged in the Northern Hemisphere troposphere in July. Maxima are in the lower troposphere mid-latitudes. Matthes et al. (2007) found values twice as high (4–12%), but again based on emission data of the year 1990. They also mention that calculated NO_x tends to be overestimated in their model compared to the observed values in high NO_x regions. Differences between the model and observed values of the NO_2 columns are 15–30%. Furthermore, we need to consider that during the period from 1990 to 2000 many relevant emissions (NO_x, CO and NMVOC) have been reduced in large parts of the industrialised world due to the widespread use of catalytic converters.

In the *Quantify* results the globally averaged impact of road traffic on ozone in the PBL is only moderate with differences in the perturbed case of 1–2 ppb. In the mid-latitudes it is most pronounced and shows a clear seasonality. The regional impact can be stronger and reaches for example 3 ppb in summer in the Eastern US and central Europe whereas Matthes et al. (2007) found even changes up to 5 ppb. It seems that in some cases the pollutants are transported downwind from the original region exhibiting a similar effect of ozone production in the downwind regions.

3.2.3. Impacts on OH

As for OH concentration, moderate changes in the monthly average are modelled for a perturbed system. While ozone is in many regions increased by transport even in winter OH varies more significantly in sign. In the NH winter road-traffic emissions slightly decrease the OH concentration due to emissions of CO and NMVOC. Both are direct sinks for OH. However, the difference between the perturbed case and the base case is less than 1%.

In NH summer the OH concentration is clearly increased, in particular over high traffic regions. This increase is 2–4% in the mid troposphere and close to the boundary layer between 20° and 60° North if scaled to 100% (reaching about 0.18% or $5 \cdot 10^3$ molecules cm^{-3} for a 5% perturbation). The reason is that OH is more effectively recycled by NO_x due to the photolysis of NO_2 and additional OH is formed from photochemically produced ozone, in particular in summer. On the other hand, the OH production is less sensitive to perturbations at the high NO_x levels in polluted regions, since the reaction of OH with NO_2 is also a sink for OH (Lelieveld et al., 2002). Therefore, in the clean marine boundary layer emission from ship transport lead to higher OH formation per molecule NO_x than road transport does. In summer, the reducing effect of CO is relatively weak and minor compared to that of NO_x. Varying OH concentrations lead also to changes in the methane lifetime as discussed in Section 4.1.

Globally averaged methane-lifetime reduction due to road-traffic emissions are estimated to be on the order of 1.6%, not including feedback factors to account for the long-term steady state (Fuglestvedt et al., 1999; Hoor et al., 2009).

3.3. Impacts on air quality and health

Air quality in most European cities does not always meet the limit values set by European regulation, and still has major negative impacts on human health and welfare. Land transport and in particular road transport has a considerable negative influence on air quality. Evidence on health impacts of air pollution has been gathered through numerous studies conducted by scientists of various disciplines and published since the late 1980s (Pope, 1989, 2000; Pope et al., 1995, 2002; Brunekreef et al., 1995; Brunekreef and Holgate, 2002; Brunekreef and Forsberg, 2005; Zmirou et al., 1998; Jędrychowski, 2000; Nyberg et al., 2000; Schwartz, 2000; Peters et al., 2000, 2001; Katsouyanni et al., 2001; Hoek et al., 2002; Leikauf, 2002; Brook et al., 2004; Boldo et al., 2006; Naess et al., 2007). The results of such studies have been condensed and comprehensively evaluated in several WHO publications (WHO, 2000, 2002, 2005a,b) and in relation to land transport impacts in WHO (2003); Krzyzanowski et al. (2005) and WHO (2006). According to WHO estimates more than 2 million premature deaths each year are attributed to urban outdoor air pollution and indoor air pollution from the burning of solid fuels. More than half of them are occurring in developing countries (WHO, 2005b). A comparison with other leading risk factors is given in Fig. 10.

Most of the air pollutants are related to respiratory and cardiovascular diseases. Some of them are also carcinogenic. Their detailed impacts, partially discussed in the above literature, are subject of comprehensive medical research and cannot be assessed in this report.

The effects of transport-related pollution can be categorized by scale in local and regional: "local" concerning urban air quality and health impacts due to particles, their toxic components and toxic short-lived gases, and "regional" pertaining to the welfare losses from acid deposition, tropospheric ozone (Faiz, 1993) and indirectly climate change.

3.3.1. Urban scale

Many regions in the world undergo increasing urbanisation and motorisation and more than half of the world's population is estimated to live in urban areas. Approximately 9% of the EU-25 population live closer than 200 m from a road with more than 3 million vehicles per year, and as many as 25% live within 500 m (EEA, 2007). The land transport directly emits primary air pollutants and precursors of secondary air pollutants. Harmful primary pollutants are particulate matter (PM), carbon monoxide (although only in high concentrations), nitrogen oxides, ammonia and non-methane volatile organic compounds (NMVOCs), such as benzene, and most polycyclic aromatic hydrocarbons (PAHs). Sulphur dioxide emissions from land transport have been strongly reduced and are now less relevant. Secondary traffic-related pollutants which often can extend from the local to the regional scale include gases such as ozone, peroxyacetyl nitrate (PAN), formaldehyde (HCHO) and secondary particles. The secondary organic aerosol (SOA) generally belongs to the fine PM mode ($PM_{2.5}$) and consists for example of sulphate aerosol or particulate nitrate organic compounds of low volatility.

3.3.1.1. Particles. In urban conditions, the particle size distributions vary rapidly in shape and magnitude following the instantaneous traffic variation and local meteorology.

The number size distribution is influenced by nucleation, coagulation, condensational growth, plume dilution, and vertical mixing during transport from the street to the urban background (Turco and Yu, 1999). The total particle number measured in urban areas often correlates well with NO_x and shows a distinct diurnal variation, indicating a common traffic source (Ketzel et al., 2004;

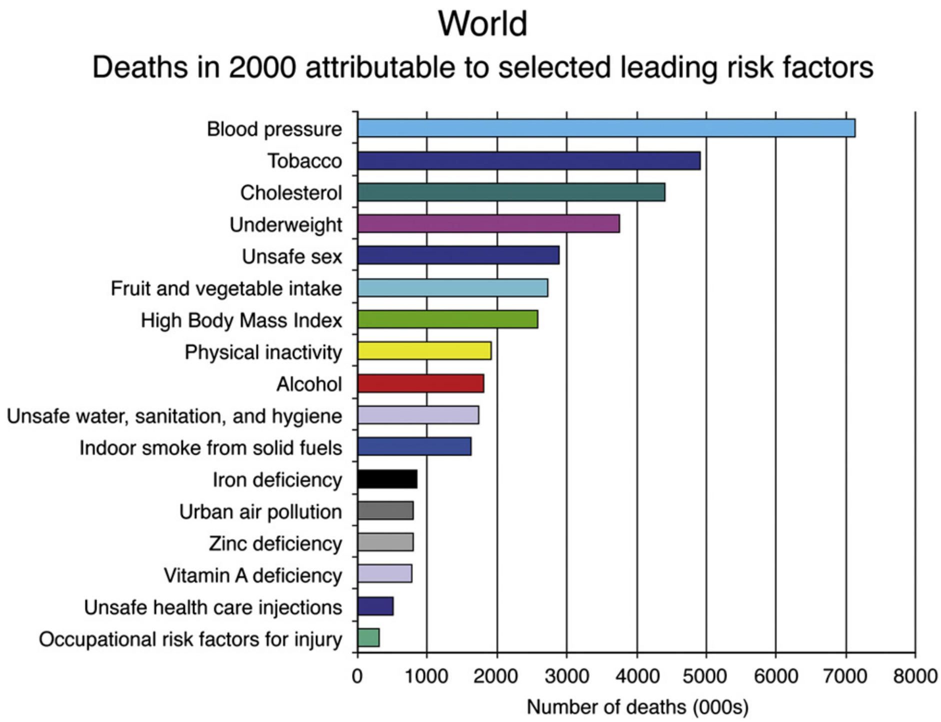

Fig. 10. Deaths in 2000 attributable to selected leading risk factors (WHO, 2002).

Hussein et al., 2004). Traffic emissions are able to affect submicron particle number concentrations around major roads and may be a dominant source of ultrafine particles ($PM_{0.1}$) in the urban atmosphere (Despiau and Croci, 2007; Rodriguez et al., 2007). For example, 1 h after a traffic peak at street level significant increases (bursts) in concentrations of particles around 30 nm have been reported. Exhaust emissions formed in the combustion processes affect mostly the particulate matter load in the fine mode. Some combustion products form also secondary particles belonging to the fine and ultrafine modes. Brake wear and wear of the road surface is an important factor for the highest concentrations in the coarse mode (Manoli et al., 2002). The contribution to particulate mass ranges from place to place from a few percent up to 80% (Almeida et al., 2005; Johansson et al., 2007). It was also found that the traffic contribution in the coarse size fraction (1.9–72 μm) was approximately 80% up to 150 m from the road, it dropped abruptly by a factor of 2 over a distance of 150–200 m and declined further to 20% at 1500 m from the road (Wrobel et al., 2000).

Out of all known air pollutants excluding dioxins, the strongest health effects are currently assigned to PM (e.g. Ibald-Mulli et al., 2002; Pope et al., 2002; Kappos et al., 2004; Dominici et al., 2006). PM is generally monitored as PM_{10}. However the levels of the finer fraction $PM_{2.5}$, if measured, give a better indication of the PM health effects. Particles physical and chemical properties as well as substances that adhere to their surfaces (as e.g. PAHs) influence their harmfulness. PM lifetime in the atmosphere differs significantly with their size. The lifetime of $PM_{0.1-2.5}$ is in the order of weeks to months – which allows them to travel over continents. In consequence, $PM_{2.5}$ can affect people living far from their emission source, but still have due to higher concentration the strongest impacts on a local scale. The coarse PM ($PM_{2.5-10}$) are more easily deposited by sedimentation and thus have rather local impacts. Particulates from traffic may contain diverse elements, as Mg, Al, Si, P, S, K, Ca, Ti, Mn, Fe, Cu, Zn and also Pb and other heavy metals (Wrobel et al., 2000).

Primary $PM_{2.5}$, which have been found to have considerable inflammatory potency, usually contain crustal material, fugitive suspended dust, organic and elemental carbon (soot), inorganic ions and heavy metals. Secondary $PM_{2.5}$ consist mainly of SOA, which can also origin from traffic (Brook et al., 2007; Rappenglück et al., 2005). Other components like sulphate and nitrate salts show lower toxic potency. PM containing As, Cr, Ni, Pb or those which bound specific PAHs (e.g. benzo-(α)-pyrene), are carcinogenic. Nitrated polyaromatic hydrocarbons (nitro-PAHs) include the most carcinogenic substances known to man and can be found in diesel exhaust fumes.

$PM_{2.5}$ are believed to be the most harmful, because when inhaled they can penetrate deep into the lungs. In particular, the effects of long-term PM exposure on mortality (life expectancy) seem to be attributable to $PM_{2.5}$ rather than to coarser particles (Brunekreef and Forsberg, 2005; WHO, 2006). Relative risks (RR) for selected pollutants estimated in meta-analysis studies prepared by WHO (Anderson et al., 2004) are presented in Fig. 11.

The average loss of life expectancy due to $PM_{2.5}$ in 2000 was estimated at 8.6 months in Europe, varying from around 3 months in Finland to 12–36 months in Benelux, Silesia and the Po Valley (Amann et al., 2004; WHO, 2006). The total number of premature deaths was estimated to be 348,000 in the 25 EU countries.

3.3.1.2. Gaseous species. Gaseous species are often monitored in air quality networks and also investigated in many single studies. Jimenez et al. (2003) demonstrated that the spatial and temporal distribution of CO and NO_x follows that of the traffic, while Pfeffer (1994) and Perrino et al. (2002) showed that the mean concentrations of gaseous pollutants at very busy junctions are considerably higher than those of areas that are not directly affected by road traffic. Ambient NMVOC levels are mainly affected by motor vehicle emissions where high levels of aromatic hydrocarbons (toluene, benzene and xylenes) have been detected and associated with diverse public transport systems (Velasco et al., 2007;

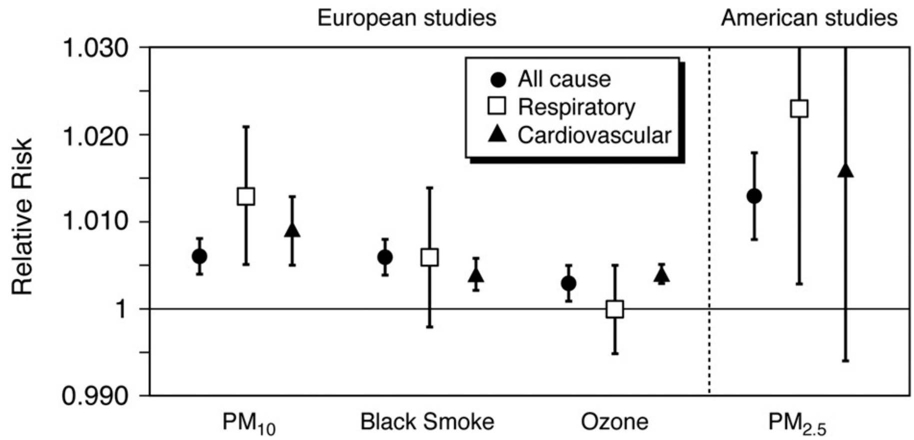

Fig. 11. Summary estimates for relative risks (RR) for mortality and different air pollutants. RR is the risk of an event (or of developing a disease) relative to exposure and is calculated as a ratio of the probability of the event occurring in the exposed group versus the control (non-exposed) group. Note: There were not enough European results for a meta-analysis of effects of $PM_{2.5}$. The relative risk for this pollutant is from North American studies (WHO, 2006 after Anderson et al., 2004).

Muezzinoglu et al., 2001). Traffic-related hydrocarbons (m, p, o-xylenes, toluene, ethene, propene) were found to be responsible for the generation of ozone impacts above 50 ppbv (Rappenglück et al., 2005).

PAHs observed concentrations were found to be associated predominantly with emissions from road traffic although other sources such as fuel oil, coal combustion, and incineration contribute as well (Marr et al., 2006; Harrison et al., 1996). The traffic contribution of PAHs to busy street air was estimated to be up to 90% on working days and 60% during weekends and its contribution to the city background air was estimated to be 40% (Nielsen, 1996). In the same study, the PAHs contribution from diesel vehicles was about 67% of the total PAHs traffic contribution.

Ammonia emissions from traffic have their origin usually in gasoline-powered motor vehicles equipped with three-ways catalytic converters (Fraser and Cass, 1998; Moeckli et al., 1996).

Photochemical models are applied based on emission inventories in order to assess theoretically the impact of traffic emissions on air quality. Comparisons to simulations without traffic emissions show that for example ozone peak values can double due to the traffic influence (Fig. 12, Borrego et al., 2000).

3.3.1.3. Ozone. Night and early morning depletion of ozone are explained by the increase of NO traffic emissions. Hourly modelling using a simple constrained chemical model showed that the NO_2/NO_x emissions ratio from road traffic has increased markedly from a mean of about 5–6 vol% in 1997 to about 17 vol% in 2003 (Carslaw, 2005). It was shown that besides from high background ozone the increased use of continuous regeneration diesel particle filters (CRT) contribute to the increasing trends in the NO_2/NO_x emissions ratio. Such filters require excess NO_2 for regeneration and prevent at the moment that the NO_x problem and the particle problem can be tackled in parallel.

Consequences of elevated ozone levels for health are respiratory diseases. At concentrations exceeding 240 μg m^{-3} (EU alert threshold for O_3) both healthy adults and asthmatics would experience significant reductions in lung function as well as airway inflammation. At lower concentrations elderly people and those with respiratory diseases are most affected. Due to its low solubility in water ozone can penetrate deep into the lungs. Tropospheric O_3 causes eye irritations and can be linked with allergy development as well as with aggravation of allergic reaction (Krzyzanowski et al., 2005). As the amount of O_3 an individual is exposed to depends on the time spent outdoors, children and people working outside are most at risk. Although health impacts of ozone have been less investigated than of PM, existing studies in Europe and beyond (e.g. Mudway and Kelly, 2000; Gryparis et al., 2004; Bell et al., 2005, 2006; Ito et al., 2005; Levy et al., 2005) show convincing, though small, positive associations between daily mortality and ozone levels, independent of the effects of PM (see Fig. 11).

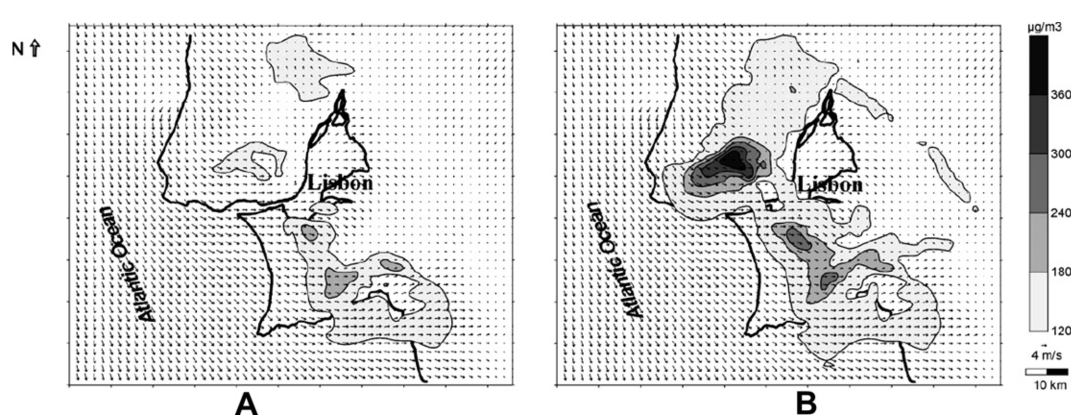

Fig. 12. Simulation results of ozone peak values in July for two emissions scenarios at Lisboa: (A) without traffic emissions; (B) with traffic emissions (Borrego et al., 2000).

3.3.2. Regional scale

While ozone peak values affect mainly the local population living in cities or the periphery, transport's contribution to the global elevation of background ozone has regional impacts.

They are primarily assessed with the help of models as described in part 3.2 of this publication. According to the EMEP 3-D Eulerian oxidant model exceedances of the accumulated exposure thresholds (AOT) of 40 and 60 ppb are substantially reduced from 1990 to 2010, assuming feasible emission reductions. But significant exceedances remain, especially in southern Europe. Reductions in road-traffic emissions beyond those included in the *Trend* scenario could still make an appreciable contribution to reducing ozone levels towards guideline values. Heavy-duty vehicles and evaporative emissions are predicted to make the largest contributions, followed by passenger car exhaust (Reis et al., 2000).

Besides from immediate health effects of air pollution, humans are also indirectly affected by damages to soils, ecosystems, vegetation, crops and water sources. Such can be a result of regionally increased ozone, which is e.g. negatively influencing crop growth. They can also result from deposition of acidifying or eutrophying nitrogen species, as well as heavy metals incorporated into PM. Finally, by its capacity to induce climate change, traffic-related CO_2, O_3 and halocarbons are likely to affect human health by climate change-related exposures. Such may be increases in heat waves, floods, storms, fires and droughts, with the consequences of malnutrition as well as the migration of some infectious diseases (IPCC Climate Change, 2007a,b,c). Due to increasing knowledge about health effects of air pollution, these effects are a bigger global issue today than they were in 20th century (Juda-Rezler, 2006).

4. Impacts on radiative forcing and climate

4.1. Impacts of greenhouse gases

The different changes in greenhouse gases that are due to land transport are briefly reviewed in this section and supplemented with results from recent literature and the *Quantify* project. *Quantify* estimates are based on 5 different models. For each of them land transport emissions haven been decreased by 5% and results are obtained by an extrapolation to 100% (see also Section 3.2 of this report).

4.1.1. Carbon dioxide

The main impact of land transport on climate comes from carbon dioxide (CO_2). Due to its long atmospheric residence time CO_2 is well-mixed throughout the troposphere and the stratosphere. As the current emissions from land transport are almost three times as large as the emissions from the aviation and shipping sectors combined (Eyring et al., 2005), its relative contribution to radiative forcing is significant. The long residence time of CO_2 also requires that the historical development of emissions are taken into account when calculating the contribution to CO_2 enhancement and thus the radiative forcing at a given point in time. The current radiative forcing by CO_2 is estimated by IPCC (2007a,b,c) to be 1.66 W m^{-2}, based on a total increase of nearly 100 ppmv since pre-industrial times. Schultz et al. (2004) estimate that surface transport (including maritime shipping) by the year 2000 had contributed 17.4 ppmv to the CO_2 increase, which would translate into a radiative forcing of nearly 290 mW m^{-2}. In a recent study Fuglestvedt et al. (2008) calculated a value of 150 ($\pm$17) mW m^{-2} from road transport and 21($\pm$3) mW m^{-2} from rail traffic. Indirect emissions related to rail traffic (production of electric power) add another 3.8($\pm$1) mW m^{-2}. In comparison, they obtain best estimates of 35 mW m^{-2} and 21 mW m^{-2} for the shipping and aviation sectors, respectively.

Future radiative forcing for a given point in time will depend on the time evolution of emissions, which in turn will reflect future policies, technologies, and economic growth. More accurate statements can be made for the future impact of current emissions on a given time horizon. Integration of the radiative forcing over a future time horizon for a one-year pulse of current global emissions can be used to compare the impact of different climate gases in units of (W m^{-2})·yr (see IPCC, 2007a,b,c; their Fig. 2.22). The contribution of each climate gas depends on the chosen time horizon and becomes relatively more important on longer time horizons in the case of a long-lived gas such as CO_2. For a detailed discussion compare also Fuglestvedt et al. (2010). Fuglestvedt et al. (2008) use emissions from the EDGAR database for 2000 and calculate that, on a 100-year time horizon, the contribution from CO_2 is nearly 400 mW m^{-2} yr for road transport, compared to about 100 mW m^{-2} yr for shipping and aviation combined. Their shipping emissions are based on own calculations consistent with Endresen et al. (2007) and their aviation emissions from Eyers et al. (2004).

4.1.2. Ozone

Ozone has a relatively short lifetime of only a few weeks in the lower troposphere and is thus non-homogeneously distributed, so that models are commonly used to calculate its global mean radiative forcing. Increases near the surface are known to have a smaller impact on radiative forcing than increases in the upper troposphere (Lacis et al., 1990; Hansen et al., 1997). Therefore, the contribution of land transport to ozone radiative forcing per kg of fuel burnt is assumed to be smaller than for aviation, although in particular in summer its impact extends to the upper troposphere.

Niemeier et al. (2006) applied a chemical transport model and emissions from the POET (Olivier et al., 2003) and EDGAR-3 (Olivier et al., 2001) databases to calculate an ozone-related radiative forcing of 50 mW m^{-2}. Fuglestvedt et al. (2008) obtain 54 ($\pm$11) mW m^{-2}, compared to a best estimate of 22 mW m^{-2} from aviation and 32 mW m^{-2} from shipping. The rail sector contributes another 2 mW m^{-2} according to their study. They also note that the radiative forcing per ozone burden change is larger for land transport than for shipping, probably because of more efficient vertical mixing occurring over land areas that extends the ozone increase towards higher altitudes (see 3.2 cross section Fig. 9).

In *Quantify*, the perturbed ozone fields were provided for detailed radiative forcing calculations (Myhre et al., in preparation). Table 10 shows results for the different models translated into the effect of total road emissions, subdivided into long-wave, short-wave and net components. Four models perturbed road emissions by a small amount to assure linearity and scaled the modelled changes in ozone to a 100% change in road emissions. The E39C model (G. Myhre, pers. Comm.) used an alternative method as described in Grewe (2007). The range of results must be seen as a measure of uncertainty in current model studies of this kind.

For future radiative forcing from ozone change, Fuglestvedt et al. (2008) obtain about 50 mW m^{-2} yr for road emissions on a 100-

Table 10
Annual-mean long-wave, short-wave, and net radiative forcings due to road emissions for the five models that participated in the first *Quantify* ozone impact calculation. Unit: mW m^{-2}.

Model	RF	TM4	OsloCTM2	p-TOMCAT	LMDZINCA	E39C
Spectrum	LW	19.6	25.5	15.6	25.5	70.4
	SW	6.7	7.2	3.6	7.4	20.9
	Net	26.3	32.7	19.2	32.8	91.3

year horizon, about as large a value as for aviation and shipping combined. Given the relatively short lifetime and inhomogeneous distribution of ozone, future changes in spatial emission distributions will alter the radiative forcing per ozone burden change, as ozone production efficiency, ozone lifetime, and its radiative forcing efficiency vary in space.

4.1.3. Methane

Methane is not emitted from road transport in significant amounts, but is changed through the emission of ozone precursors. Depending on the NO_x/VOC and NO_x/CO ratios in the exhaust gases, NO_x emissions tend to increase OH as described in Section 3.2. OH stands for the main loss of methane in the atmosphere. Also ozone produced from emissions of NO_x and other ozone precursors increases OH levels. Resulting reductions in the lifetime of methane in part offset the positive radiative forcing of ozone. The changes in methane lifetime, translated into the impact of total emissions from each transport sector, are shown in Table 11 for the road sector and all transport sectors combined as calculated in *Quantify*.

The models predict reductions in methane lifetime between one and two percent. This impact compared to the total impact from transport is not as large as the fraction of road emissions within the transport emissions. In particular, for road emissions the models calculate a much smaller impact on methane lifetimes than for a corresponding reduction in ship emissions. This is mainly due the high NO_x/CO and NO_x/NMVOC ratios in shipping emissions, and the generally low NO_x levels in marine areas.

Fuglestvedt et al. (2008) calculated the radiative impact of methane change due to each transport sector and obtained negative radiative forcings of -12 mW m^{-2} for road transport, -43 mW m^{-2} from shipping and -10 mW m^{-2} from aviation. Although uncertainties exist in terms of the exact magnitude of the impact all models agree on the partial offset of the positive ozone radiative forcing by the reduction in methane lifetime. This offset appears to be smaller in relative terms for the road sector than for the shipping and aviation sectors.

4.1.4. Nitrous oxide

The global warming potential of N_2O is larger than that of CO_2 and indirect emissions from biofuel production may increase in the future. Nevertheless, its impact on climate is estimated to remain small. According to Fuglestvedt et al. (2008) even on a 100-year time horizon the radiative forcing from current N_2O emissions from road transport will be less than 1 mW m^{-2} and thus negligible compared to the other forcing agents (Fuglestvedt, pers. comm.).

4.2. Impacts of halogenated compounds

Halogenated hydrocarbons (or "halocarbons") are efficient greenhouse gases. However, their impact on the climate system and radiative forcing is not only due to their global warming potential but also indirectly due to their ozone depletion potential.

Table 11
Methane lifetime in the base case (years), and reductions in methane lifetime in percent due to road emissions (second row) or due to road, aviation, and shipping emissions combined (third row), calculated by the *Quantify* models.

Case	TM4	Oslo CTM2	p-TOMCAT	LMDz-INCA
Base	9.0924	7.5838	11.562	9.129
Road	−1.9	−1.4	−1.6	−1.1
Road + Air + Ship	−7.2	−5.8	−9.5	−4.6

4.2.1. Contribution of mobile air conditioners (MAC) to global warming

The global warming contribution from mobile air conditioners has two origins. The carbon dioxide emission due to the increase in fuel consumption is already included in the total carbon dioxide emission estimate for vehicles. However, direct emissions from the release of the refrigerants in MAC, dominate. Their contribution to the forcing depends on their global warming potentials (GWP).

On a 100-year time horizon, the GWP of CFC-12 is 10,900, while that of the replacing HFC-134a is 1430 (IPCC Climate Change, 2007a,b,c, WG I, Table TS.2), as the lifetime of HFC-134a amounts to only 14 years (WMO, 2002, Tables 1–6). This implies a reduction of the climate impact per tonne of chemical used, and the burden for the atmosphere measured in CO_2 equivalents is decreasing (Fig. 13), although the total amount of refrigerants produced is continuously increasing (see Section 2.5, Fig. 5 and inset in Fig. 13).

Annual emissions from MAC in CO_2 equivalents (CO_2-eq) are estimated to stablise at about 280 Tg CO_2-eq per year in 2010. For 2003, 612 Tg CO_2-eq are estimated of which 514 Tg came still from CFC-12. Such amounts are clearly relevant for global warming. The 700 Tg CO_2-eq from mobile air conditioning in 2002 correspond to 17% of the estimated 4300 Tg CO_2 emitted by road transport in 2000 (see Section 2.2), or 2.7% of the 26.3 Pg CO_2 from anthropogenic fossil fuel use and cement manufacture in 2002 (CDIAC website, Marland et al., 2007). CFC-12 and HFC-134a, used in mobile air conditioners, lead to radiative forcings of 170 mW m^{-2} and 5.5 mW m^{-2} in 2005, respectively (IPCC, 2007a,b,c).

For the future a larger share of HFC-152a (difluoroethan, CHF_2CH_3) is planned. This is a halogenated compound with a global warming potential of 140, which is nearly 10 times lower than that of HFC-134a. Moreover, modern air condition systems are in general better sealed than the older ones, implying less need for refilling during the lifetime of the vehicle. The replacement of HFCs with CO_2 in the next generation of cars implies reduced emissions in terms of CO_2 equivalents due to the relatively lower GWP value of CO_2 compared to CFCs and HFCs. But at present and in the near future MAC have a significant market share in the use of halocarbons. Even when taking into account the expected decrease in emissions, MAC would still contribute about 10% of the CO_2 equivalents that are due to global transport between 2010 and 2015 (Fig. 14).

It is not sure how MAC are going to develop if there are strong changes in the powertrain technology they are connected with and if Diesel and Otto engines are going to be completely replaced. For the near future a US EPA model study estimates that the global HFC

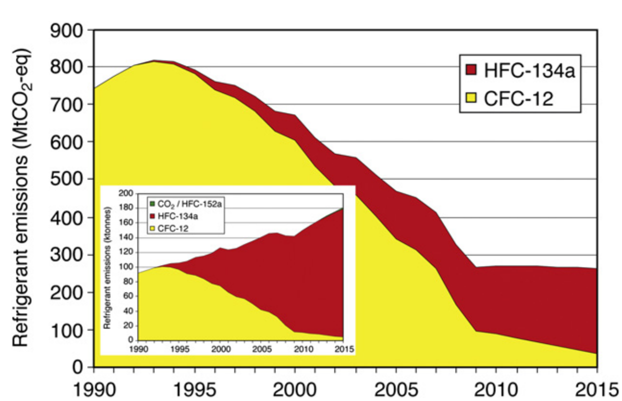

Fig. 13. SROC (2006), Fig. 6b. MAC refrigerant emissions in CO_2-eq from 1990 to 2015. CFC-12 and HFC-134a emissions are transformed into CO_2-eq based on their GWP, as given in the IPCC Second Assessment Report (IPCC, 1996; Clodic and Palandre, 2004).

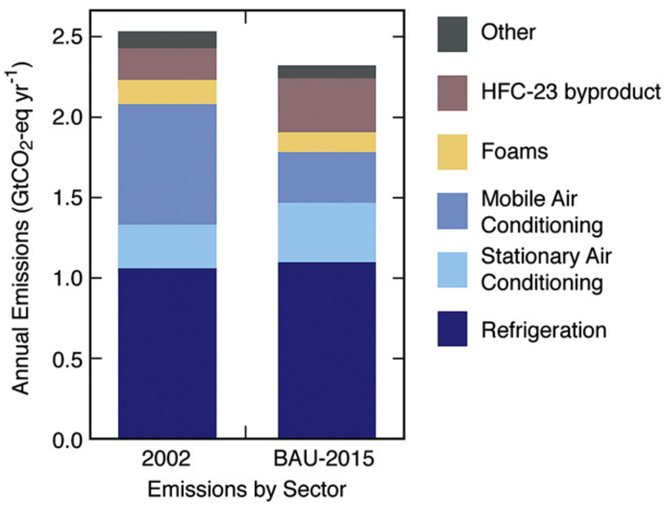

Fig. 14. Historical data for 2002 and Business-As-Usual (BAU) projections for 2015 of greenhouse gas CO_2-equivalent direct annual emissions, related to the use of CFCs, HCFCs and HFCs. SROC (2006) fig. SPM-4.

emissions, which replace CFC and HCFC emissions, will rise strongly from 117 Tg CO_2-eq in 2000 to 627 Tg CO_2-eq in 2020, of which still more than two thirds are emitted in OECD countries. The MAC shares of emissions in the US (and other Annex I countries) are going to decrease from 36% (47%) in 2005 to 20% (37%) in 2020, but in China and India they are expected to increase from 41% to 66% (DeAngelo et al., 2006, Section IV.2).

4.2.2. Impacts on ozone depletion

Regarding the protection of the stratospheric ozone layer, the transition from CFCs-12 to HFC-134a in the early 1990s, which is now completed also in developing countries, is a clear progress. HFC-134a is estimated not to have an ozone depleting potential.

This means that the threat for the ozone layer derives primarily from banks of CFC-12. Banks are the total amount of substances contained in existing equipment, chemical stockpiles, foams and other products not yet released into the atmosphere. Because of the long atmospheric lifetime (100 years) and high ozone depletion potential (0.82) of CFC-12 these banks and present emissions will continue to contribute to ozone depletion in the coming decades. CFC-12 makes the largest contribution to stratospheric chlorine levels, about 28% estimated for 1998 (WMO, 1998) and is just about to peak in the atmosphere.

The stratospheric ozone depletion (about 3% since 1980) has led to a stratospheric cooling of about 0.6 K per decade and a negative radiative forcing of about -150 W m^{-2}.

The total CFC-12 indirect forcing from all sources contributes -34 mW m^{-2} to this value for the time 1980–2000 (SROC, 2006 Chapter 1). This compensates only for 25% of the 140 mW m^{-2} due to the CFC-12 positive RF for the time 1970–2000. Therefore, the negative RF contribution from MAC through ozone depletion is of less relevance than the direct positive contribution to global warming discussed above. From 1990 to 2000 MAC contributed about one third to the total CFC-12 emissions, but in the decades before clearly less than one quarter. Therefore the negative radiative forcing from MAC can be estimated to be smaller than -10 mW m^{-2} for the time 1980–2000.

Although there are high uncertainties in such estimations and also in projections for the global warming contribution it seems clear that the impacts from mobile air conditioners remain to be relevant in the future, primarily for climate change and to a much lesser extent for ozone depletion.

4.3. Impacts of aerosol on radiative forcing

Aerosols from land transport interact with the radiation passing the atmosphere trough reflexion, scattering or absorption and therefore have an impact on the radiative forcing. Balkanski et al. (2010) compared the results of three models with different radiative and aerosol codes to estimate the contribution to the radiative forcing of the aerosol produced through road activities. All three models show maxima for the total sum of the black carbon (BC), organic carbon (OC) and sulphate direct aerosol effect at Northern mid-latitudes and also over North Africa and the Arabian Peninsula, regions with relatively low cloud cover. Other regions where maxima occur as a consequence of activities from road transport are: Western and Central Europe, Eastern US, South Asia and Eastern China. Not surprisingly, these regions are also where the highest emissions take place (Fig. 15). The aerosol radiative forcing from road transportation is dominated by black carbon. Fig. 15

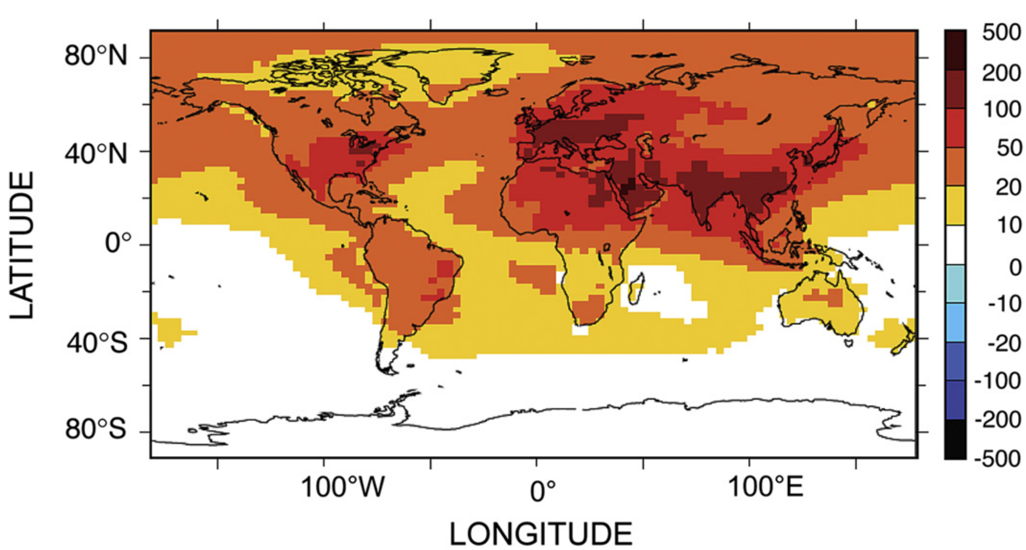

Fig. 15. January top of the atmosphere radiative forcing (mW m^{-2}) due to black carbon emitted from road transportation.

Table 12
Mass emitted, loads and aerosol optical depth, direct radiative forcings for the transport sector. Standard deviation for external and internal mixtures comes from the results of two difference models described in Balkanski et al. (2010).

	Emissions (Ktonnes yr^{-1})	Column Burden ($\mu g\ m^{-2}$)	Optical depth ($\times$1000)	External mixture ($mW\ m^{-2}$)	Internal mixture ($mW\ m^{-2}$)	Range[b] published by Fuglestvedt et al. (2008)
Internal BC	721.6	36.0	0.184	$+31.7 \pm 10.7$	$+43.5 \pm 12.3$	$+23 \pm 9$
OC	326.7	6.88	0.077	-2.4 ± 1.4	-2.4 ± 1.4	-8 ± 4
SO_4	1894.6[a]	9.8	0.530	-9.4 ± 2.5	-9.4 ± 2.5	-12 ± 5
Total				**+19.9 ± 11.1**	**+31.7 ± 12.6**	**+3 ± 11**

[a] Emissions are calculated for SO_2; load, optical depth and radiative forcing are calculated for sulphate.
[b] The ranges reported here were obtained through Monte Carlo simulations that included uncertainties in emissions (see Table 3 of the Supplementary Material in Fuglestvedt et al., 2008).

shows its geographical distribution for January. Black carbon's top of the atmosphere yearly averaged forcing is +31.7 mW m^{-2} when aerosols are assumed to be externally mixed and +43.5 mW m^{-2} when they are considered internally mixed. The column burden of organic carbon produced from road traffic is about 6 times less than of black carbon (Table 12). The radiative forcing of organic carbon from road traffic is small (−2.4 mW m^{-2}) in comparison to BC or sulphate. The radiative forcing calculated for sulphate aerosol amounts to −9.4 mW m^{-2} when averaged globally.

4.3.1. Comparison with previously published results

Köhler et al. (2001) did a rough calculation based upon a simplified description of the BC cycle and assumed emissions of BC from roads that are 3 times the inventory from Borken et al. (2007). They estimated a direct radiative forcing (DRF) for BC of 80 mW m^{-2}. If we scale the amount of black carbon that is used by these authors to that used in the present study, the DRF obtained is 27 mW m^{-2} in good agreement with the results presented here for the external mixture. Fuglestvedt et al. (2008) computed the radiative forcing for both well-mixed greenhouse gases and aerosols emitted from the transport sector. Aerosol radiative forcings were estimated based upon a global 3D simulation from the Oslo-TM2 chemical transport model. The model was run for 18 months, the first 6 months were used to initialise the aerosols fields and the last 12 months used to estimate this forcing. In addition an uncertainty range representing one standard deviation was estimated for these distributions. This uncertainty estimate takes into account uncertainties in fuel consumption, emission factors, atmospheric transport and removal as well as radiative forcing. The radiative forcing for OC in this study is substantially weaker than in Fuglestvedt et al. (2008). The mean estimate for BC (external mixture) in this study is stronger than in Fuglestvedt et al. (2008). Fuglestvedt et al. (2008) compared UiO model to previous results from the literature and estimated a range of the radiative forcing of BC from road activities. This range estimated is from 14 to 32 mW m^{-2}. The results reported here indicate higher values from 24.4 to 57.6 mW m^{-2} when both externally and internally mixed BC is considered.

Ammonia from traffic is produced mainly by cars equipped with catalytic converters. Concentrations of ammonia are 5–10 times higher at sites influenced by traffic than at rural sites (Perrino et al., 2003). Locally the presence of high ammonia concentrations could contribute by complexation with salt to nitrate formation. To our knowledge the importance on the global scale of the land traffic has not been estimated.

These results can be put in perspective by comparison with the radiative forcing of total fossil fuel emissions. For black carbon, Forster et al. (2007) report in chapter 2 of the IPCC (2007a,b,c) report a direct black carbon radiative forcing estimate from fossil fuel of 200(±100) mW m^{-2}. We infer from the numbers reported here that road traffic represents 7–16% of the total fossil fuel radiative forcing.

4.4. Effects on visibility, clouds and cloudiness

Besides from the direct effect, aerosol can influence radiative forcing indirectly via its influence on transparency of the atmosphere and changes in cloud cover and cloud properties. However, there is no evidence that land transportation has a similar effect on cloudiness as observed on low stratus clouds for ship transportation (Eyring et al., 2010), or high level cirrus clouds for aviation (Lee et al., 2010). For sure, land transport has besides from pollution and health impacts also an influence on visibility at surface level which are mixed with impacts of other sources of pollutants.

For example, in connection to the dramatic increase of vehicles in Chinese cities in the 1990s the deterioration of visibility is analysed by Song et al. (2003a). High concentration of $PM_{2.5}$ is measured both in the summer and winter (a daily average of 60–80 $\mu g\ m^{-3}$) and direct inverse correlation between visibility and concentrations of $PM_{2.5}$ during the period 1999–2000 for every season is shown in Song et al. (2003b) as well as on an hourly basis for selected episodes by Bergin et al. (2001). Source apportionment of fine-particle pollution based on a measurement campaign and a modelling study for selected sites in Beijing (Zhang et al., 2004) provides evidence of road transport impacts: about 15% of $PM_{2.5}$ stem from mobile sources accompanied by about 21% of secondary road dust. NPRI (2006) is addressing the issue of road dust impact to the environment, with respect to the visibility problem emphasising the role of $PM_{2.5}$, which is close to the wavelength of the visible spectrum and thus affecting not only the visibility range, but the colour, clarity and contrast of scenes (Malm et al., 2000a,b). Projects like MILAGRO have been studying extensively the environmental impact of a megacity urban environment at regional scale. Detailed measurement of the aerosol composition with its $PM_{2.5}$ fraction is described by Moffet et al. (2008). Stone et al. (2008) provide source apportionment analysis and conclude that during MILAGRO in the Mexico City area motor vehicles account for about 47% of the ambient organic carbon at the urban site and 31% at the peripheral site.

It must be assumed that such road transport-related aerosol burdens have indirect effects on cloud development and radiative forcing. Compared to shipping and aviation, their role might be less relevant in relation to greenhouse gases, since over land the conditions for condensation processes are not comparable to those in ship tracks or contrails. On the local scale, for example Schwarz et al. (2007) found in the Houston area of 4 million inhabitants that the black carbon heating effect due to an about 25% enhancement of BC absorption is not large enough to impact the tropospheric stability significantly. It might play some role in bigger megacities like Mexico City or New York area. The real impact of aerosols included in a computation by Jiang and Feingold (2006) for warm convective clouds is shown to be different for the case of direct effects included or not. There is negligible effect on cloud fraction and cloud depth when only indirect effects are taken into account, but the optical depth of clouds is increasing with higher droplet concentration. When direct effects and the dynamical coupling are included, the blocking of solar radiation, the further cooling of the surface and heating of aerosols contribute to the stabilisation of the atmosphere. This results in a decrease of the cloud fraction and cloud depth. These effects play a much more significant role than aerosol–cloud processes themselves. However, permanent changes in the aerosol composition and mixing from different sources in the continental boundary layer will make it difficult to attribute a radiative forcing value to the land transport sector for such indirect effects. Respective global estimations are not yet available.

4.5. Climate change and future impacts

In 2004, road transport made up for 4.7 Pg CO_2, which is 17% of the global energy-related CO_2 emissions and about three quarters of the total transport emissions of 6.2 Pg CO_2 (IPCC Climate Change, 2007a,b,c, WG III, Chap.5). Current emissions from transport are responsible for 17% of the integrated net forcing over 100 years from all current man-made emissions. Land transport gives a CO_2 forcing of 150(±17) mW m^{-2} from road vehicles and 25(±7) mW m^{-2} from rail (direct + indirect), which is together 12% of the total man-made CO_2 forcing since pre-industrial times. Furthermore, road transport is responsible for 15% of the total man-made ozone forcing, about 54(±11) mW m^{-2} (Fuglestvedt et al., 2008).

The dominating amount from road transport accumulated during a relatively short high emission history of not much more than 50 years. Transport has at the moment the highest growth rate among all end-user sectors. Therefore, the relevance for climate change will increase, in particular in developing countries.

The share in CO_2 emissions of non-OECD countries is 36% now and is expected to increase rapidly to 46% by 2030 (IPCC Climate Change, 2007a,b,c, WG III, Chap.5). In Eastern Asia the NO_x and CO_2 emissions from road transport doubled from 1990 to 2000.

Due to the enormous dynamic in growth just in the recent years and diverse alternative technologies discussed present projections do not dare to give an outlook beyond 2050. But, unless there is a major shift away from current patterns of energy use, total transport energy use and carbon emissions is projected to be about 80% higher by 2030 compared to 2004 values (IPCC Climate Change, 2007a,b,c, WG III, Chap.5), most coming from land transport. In 2050, as much as 30–50% of the total CO_2 emissions are projected to come from the transport sector (JRC/CONCAWE/EUCAR, 2006). Details about the present scenarios are described in Sections 5.5 and 5.6.

From this it is clear that the climate impact of transport will be primarily based on long-lived greenhouse gases, in particular carbon dioxide. Since mitigation is easier to realise for stationary energy consumers, the relative share of the road transport contribution to global warming is going to grow. Therefore, general climate impacts as described in the recent IPCC Climate Change (2007a,b,c) report's scientific basis will be soon attributable with a more than 20% fraction to road transport.

Expected impacts according to IPCC Climate Change (2007a,b,c) summary for policymakers are for example a temperature increase of about 0.2 °C per decade in the global average. Land surface will warm stronger. The Arctic regions are most affected, changing in turn the conditions for land transport. Winter road conditions in higher latitudes could improve, with consequences in commercial activities (see ACIA, 2004, www.acia.uaf.edu). Opposite, in permafrost zones negative effects might appear with higher temperatures shortening the winter-road season (Instanes et al., 2005). A sea level rise between 18 and 59 cm until the end of the century is expected and an additional sea level rise due to rapid melting of glaciers in particular in the Arctic is possible, affecting coastal settlements and transport infrastructure. Sea ice is going to shrink and snow cover is projected to contract. This leads to reductions of the Earth albedo. The warming of the oceans favours stronger tropical cyclones leading to higher damage in coastal regions. Since warmer air holds more water the water cycle is going to intensify, leading to stronger rain events and higher evaporation. Since increases in rainfall will be unevenly distributed, some regions are going to experience more severe droughts. Extreme precipitation and storms could e.g. imply in traffic limitations, road and railroad closures, train delays and cancellation (O'Brien et al., 2004).

It is hardly predictable, to what extent aerosol emissions from road transport will contribute to the global energy balance as part of the direct or indirect aerosol effect. Since the major forcing comes at the moment from black carbon, the present effect is positive. However, particle emissions are highly undesirable due to their negative health impacts. They have already been significantly reduced and will be more reduced according to more strict emission regulations in the near future. The lifetime of particles is short. Therefore, particle impacts are not going to make a large contribution to the long-term positive radiative forcing effects as shown in Fig. 17.

Radiative forcing values as shown in Fig. 16 are useful to evaluate the impact of historical emissions on climate until present. However, they are not necessarily useful to evaluate impacts of present and future emissions on the future climate. Decision making for the future requires other metrics as discussed in Fuglestvedt et al. (2008). Their applicability depends on the purpose. UNFCCC decided to use the Global Warming Potential with a 100-year time horizon (GWP_{100}) in the Kyoto Protocol. Shine et al. (2005, 2007) have proposed the Global Temperature Potential (GTP) as an

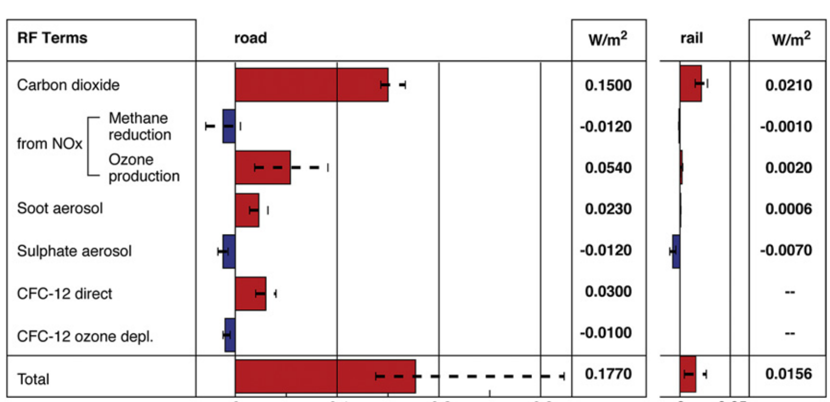

Fig. 16. Radiative forcing for road and rail transport in 2000.

Table 13
Emission metrics (GWP_{20}, GWP_{100}, GTP_{20}, GTP_{50}, GTP_{100}) and corresponding CO_2-equivalent emissions (in Gg (CO_2)/yr for all metrics) for the various components of road transport emissions. GWP and GTP data are taken from Fuglestvedt et al., 'Metrics' assessment in this issue. Detailed information about calculations and sources of the GWP and GTP values are given there.

	GWP_{20}	GWP_{100}	GTP_{20}	GTP_{50}	GTP_{100}	CO_2-eq emissions (GWP_{20}-based)	CO_2-eq emissions (GWP_{100}-based)	CO_2-eq emissions (GTP_{20}-based)	CO_2-eq emissions (GTP_{50}-based)	CO_2-eq emissions (GTP_{100}-based)
CO_2	1	1	1	1	1	4174	4174	4174	4174	4174
NOx	19	−11	−87	−29	−2.9	169	−98	−772	−257	−26
CO	6.0	2.0	3.7	0.77	0.29	655	218	404	84	32
NMVOC	14	4.5	7.5	1.5	0.66	191	61	102	20	9
Soot BC	1600	460	470	77	64	1107	318	325	53	44
Soot OC	−240	−69	−71	−12	−10	−73	−21	−21	−4	−3
SOx dir.	−140	−40	−41	−6.9	−5.7	−262	−75	−77	−13	−11
CFC-12	11000	10900	11500	11800	9200	658	652	688	706	550
HFC-134a	3830	1430	3140	795	225	253	94	207	52	15

emission metric going one step further in the chain from emission values to concrete consequences of climate change. It is consistent with the policy target of constraining the global mean surface temperature increase below a threshold (e.g. the EU's target of keeping it below 2 °C above pre-industrial levels). Tables 12 and 13 and Fig. 17a,b show the GWP_{20}, GWP_{100}, GTP_{20}, GTP_{50}, GTP_{100} and CO_2-equivalent emissions for these metrics for the various components of the land transport emissions. Details on input data and how the metrics are calculated are given in Fuglestvedt et al. (2008).

Fig. 17 demonstrates a clear difference between short term and long-term impacts. In the short term, two factors play a major role additionally to the CO_2 effect: 1) Methane is increased by CO emissions and decreased by NO_x emissions via OH reduction or formation, resulting in warming or cooling impacts. 2) Aerosols can either cause a warming, if they consist of black carbon (BC), which is an important short term factor, or cause a cooling if they consist of sulphate, which is a less important opponent in land transport. Both effects become significantly weaker in their GWP if a 100-year time scale is considered and are nearly negligible if the global temperature potential is estimated. For the long term only very long-lived GHG play a role: CO_2 and to some extent CFC-12 from air conditioners.

5. Future developments

5.1. Present standards and regulations

The European Union regulates land transport-related air emissions by automobile emissions standards (Euro) and by automotive fuel quality standards. Emissions from road vehicles are regulated individually for light-duty vehicles (LDV = cars and light vans) and for heavy-duty vehicles (HDV), i.e. road vehicles heavier than 3.-5 tonnes (trucks and buses). A whole series of amendments have been issued to stepwise tighten the limit values. Also non-road vehicles and machinery, as well as two- and three-wheeled vehicles have been included. The first set of modern European emission standards, Euro 1, entered into force in 1993. Euro standards regulate the emissions of nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO) and particulate matter (PM) over a standardised drive cycle and are expressed in mg of pollutant per km (LDV) or per kWh (HDV). All vehicle types must be tested in order to obtain a type approval. On April 2009 a new Regulation (EC) No 443/2009 limiting CO_2 emissions from new passenger cars was adopted at EU as one of six legislations that make up the EU energy and climate package. Average CO_2 emissions from all new cars sold in the EU should come down to 130 g km^{-1} by 2015. There is also a non-binding long-term objective of 95 g km^{-1}, to be attained by 2020.

For LDV, the emission standard so far in force was Euro 4 (since 2005) defined by Directive 98/69/EC. Diesel vehicles were allowed to emit around three times more NO_x than gasoline. Emissions of PM from gasoline vehicles are not regulated since they are very low. Since September 2009 Regulation (EC) No 715/2007 defining the Euro 5 and Euro 6 standards is applied. Euro 5 will define standards for PM, HC and NO_x from 2009 for new models with the main goal of a large reduction of PM emission from diesel cars. Euro 6 is scheduled to enter into force in September 2014 and shall further reduce the emissions of NO_x from diesel vehicles (Table 15). However, recent studies have shown that it might be difficult to comply with the air quality limit for NO_2 which shall be reduced in parallel from 180 mg km^{-1} to 80 mg km^{-1}. A higher share of so-called "direct NO_2 emissions" have been observed for modern diesel passenger cars and heavy-duty vehicles using standard particle filter systems (Palmgren et al., 2007). For comparison, the US state of California along with ten other US states, has currently a much tougher NO_x standard of approximately 40 mg km^{-1}.

Concerning regulations for HDV, Euro IV was in force since October 2005 and Euro V – since October 2008. In December 2007 the EU Commission presented a proposal for the Euro VI standard and put forward four different suggestions, considering different fuel types, for stakeholder consultation (Elvingson, 2007). The proposed diesel engine standards (EU A–EU D) are compared to the

Table 14
Emission metrics (GWP_{20}, GWP_{100}, GTP_{20}, GTP_{50}, GTP_{100}) and corresponding CO_2-equivalent emissions (in Gg (CO_2)/yr for all metrics) for the various components of rail emissions. GWP and GTP data are taken from Fuglestvedt et al., 'Metrics' assessment in this issue. Detailed information about calculations and sources of the GWP and GTP values are given there.

	GWP_{20}	GWP_{100}	GTP_{20}	GTP_{50}	GTP_{100}	CO_2-eq emissions (GWP_{20}-based)	CO_2-eq emissions (GWP_{100}-based)	CO_2-eq emissions (GTP_{20}-based)	CO_2-eq emissions (GTP_{50}-based)	CO_2-eq emissions (GTP_{100}-based)
CO_2	1	1	1	1	1	119.7	119.7	119.7	119.7	119.7
NOx	19	−11	−87	−29	−2.9	7.49	−4.33	−34.28	−11.43	−1.14
Soot BC	1600	460	470	77	64	175.28	50.39	51.49	8.44	7.01
Soot OC	−240	−69	−71	−12	−10	−11.49	−3.3	−3.4	−0.57	−0.48
SOx dir.	−140	−40	−41	−6.9	−5.7	−84	−24.0	−24.6	−4.14	−3.42

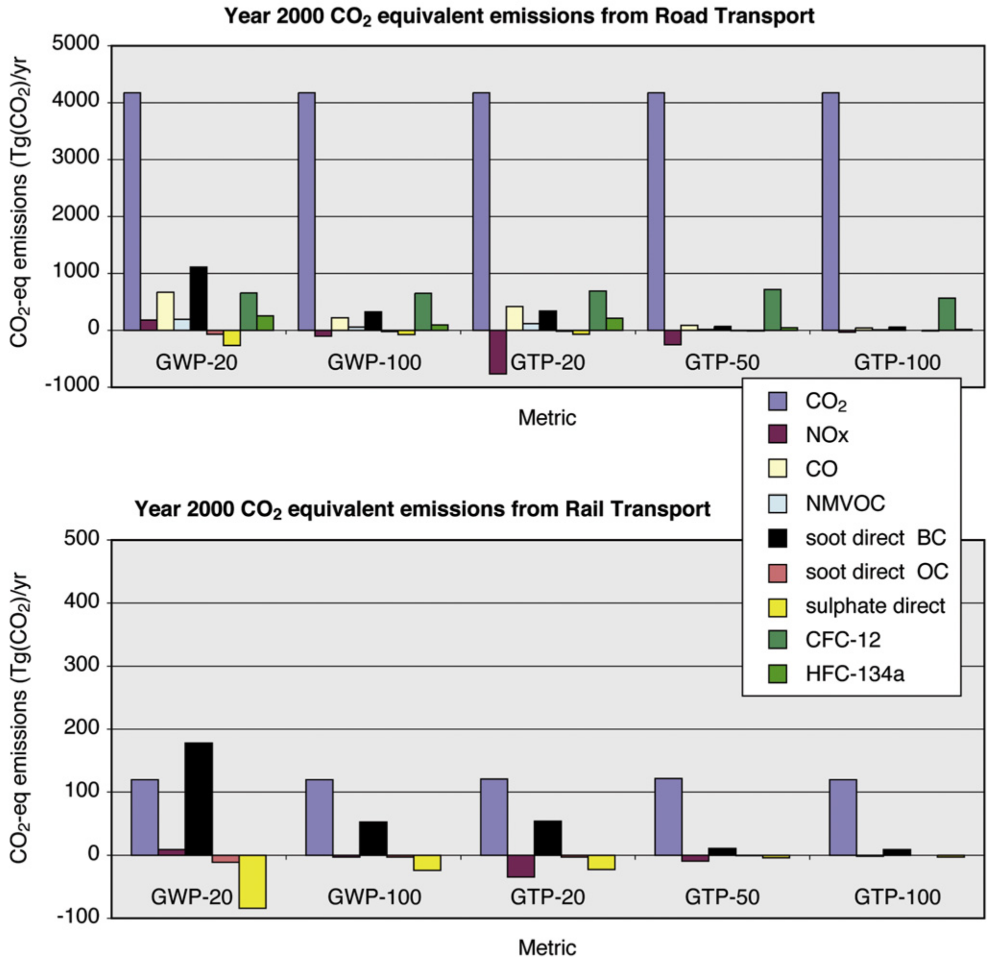

Fig. 17. a and b: Short term and long-term global warming potentials (GWP) and global temperature potentials (GTP) of emissions from road transport (above) and rail transport (below) given in Tables 13 and 14. Please note the one order of magnitude difference in the y-axis..

Japanese and US requirements for HDV in Fig. 18. In June 2009, scenario EU A which represents the close global harmonisation with forthcoming US and Japanese standards, was adopted for Euro VI in EC Regulation 595/2009. It sets NO_x emission limit at 0.4 g kWh^{-1} and PM mass limit for 10 mg kWh^{-1}. This would require a higher rate of cooled exhaust gas recirculation (EGR) in addition to the use of a more efficient selective catalytic reduction (SCR) system.

As for fuel quality, common EU specifications for gasoline, diesel and gasoil used in road vehicles, inland waterway barges and non-road mobile machinery have been set by the Fuel Quality Directive 98/70/EC amended by 2003/17/EC Directive. They focus mainly on sulphur and for gasoline on lead and aromatics. Since 1 January 2002 all gasoline sold in the EU is unleaded, while the limit on the sulphur content of gasoline and diesel is 50 ppm since 1 January 2005. 1 January 2009 maximum sulphur content for diesel and petrol is lowered to 10 ppm. Also the maximum permitted content of polyaromatic hydrocarbons (PAHs) in diesel is reduced by one third, i.e. to 8% by mass.

Table 15
The new Euro standards [mg km^{-1}] for NO_x and PM from passenger cars (Acid News, 2007).

	Euro 3	Euro 4	Euro 5	Euro 6
Obligatory for new cars	2000	2005	Sept 2009	Sept 2014
NO_x – diesel cars	500	250	180	80
NO_x – petrol cars	150	80	60	60
PM – all cars	50	25[a]	5	5

[a] Diesel cars only.

5.2. Vehicle technologies

Today, almost all road vehicles worldwide and to some extent trains as well are propelled by internal combustion engines which convert the chemical energy of the fuel into mechanical energy at the wheel. Greenhouse gas emissions result mainly from the combustion of carbon containing fuels. Reduction of GHG emissions is possible by (a) lowering energy consumption by improving the drivetrain efficiency, (b) by reducing vehicle energy demand and (c) using alternative drivetrains.

5.2.1. Improving drivetrain efficiency

Gasoline engines today are dominated by the homogenous charge stoichiometric combustion process. They work well with a three-way catalyst to reduce air pollutant emissions (Eichlseder and Blassnegger, 2006). Measures to reduce fuel consumption near to mid-term aim to (1) improve part load efficiency (e.g. downsizing with turbocharging, cylinder deactivation), (2) tackle throttle losses by direct injection of fuel and variable valve control, (3) improving high pressure efficiency and (4) address power losses

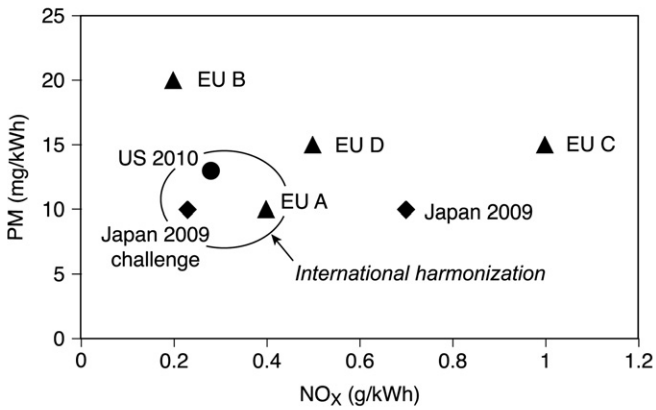

Fig. 18. Current standards and proposed scenarios for HDV standards (Elvingson, 2007).

through e.g. friction or auxiliary units. Several studies examined CO_2 reduction of individual measures (e.g. Atkinson et al., 1999; NRC, 2002; Smokers et al., 2006). Fuel consumption improvements, related to the New European Drive Cycle (NEDC), of up to 25% at the same driving performance for European middle class vehicles have been demonstrated (Fraidl et al., 2007). Fuel economy of diesel engines in real world driving however cannot be reached due to thermodynamic reasons. Diesel engines have already been improved in the past, e.g. by direct injection, and therefore offer a lower potential for improvements. Still, downsizing with turbocharging and reduction of friction losses may lower fuel consumption also in Diesel engines.

Transmissions are inevitable for internal combustion engines (ICE). They operate at speeds higher and torques lower than those requested at the vehicles wheels (Kasseris, 2006). Optimised gearboxes and dual clutches can improve fuel economy by 1–5% (Smokers et al., 2006).

Hybrid drivetrains consist of at least two different energy converters and two energy storage components. There are several different hybrid architectures in combination with ICE and levels of hybridisation. The latter is distinguished by the power of the electric motor. Hybrid drivetrains make use of engine displacement downsizing and automated gearswitch. Advantages are recuperation of brake energy, enhanced driving performance and improvements in engine efficiency due to downsizing. Disadvantages are higher costs, added system complexity and increase of vehicle weight.

Hybrid vehicles are available since the 1990ies. In 2006 approximately 400,000 hybrid cars were sold which is less than 1% of the world car production. For the future, an increasing number of hybrid models are announced. The energy savings potential is reported for low hybridisation (start-stop) and driving within cities between 3% and 12% (Japan) and for full hybrid vehicles 19% in US Highway cycle and 44% in the US City and NEDC cycle (Schmidt, 2006).

Different hybrid architectures, omitting direct mechanical link of ICE and wheels by a pure electric drive are also proposed (series hybrid). This includes so-called range-extender or plug-in hybrids where the ICE/generator on board is used to recharge the battery at high efficiency while the battery can also be charged from the power grid.

Alternative concepts are combustion engines like free piston engines with linear alternators, which directly produce electricity without driving a conventional generator (Achten et al., 2000; Max, 2005; Pohl and Gräf, 2005).

Recovery of waste energy is a way less well explored to improve engine efficiency. Only 25–35% of the chemical energy in the fuel is converted into mechanical energy by the engine. The rest is lost as heat in the engine cooling system and the exhaust. 1–2% can be recovered today e.g. through thermal electric generators (Thacher et al., 2007), fuel economy improvements of up to 5% are projected (Friedrich et al., 2007).

Reductions of the vehicle energy demand are possible by influencing three factors: inertia weight, aerodynamic drag and rolling resistance.

Lightweight construction to lessen vehicle mass is a prominent example, tackling power needs to accelerate and to climb. 100 kg less weight leads to reductions of between 4 and 17 g CO_2 km^{-1} (Espig et al., 2006). Higher strength steels as well as lightweight materials as Aluminium, Magnesium, glass fibre and carbon fibre reinforced plastics are already used to some extent in vehicle structures today. Further potential to reduce 60–120 kg for a mid-size car has been shown with additional costs of 100€ to approx. 800€ (SLC, 2007).

Rolling resistance depends on the material of the tire, the construction of the tire and the radius, tire pressure and driving speed. Studies indicate that tire pressure should be increased by 0.02–0.04 MPa which would lower fuel consumption by 1–2.5%. Tire industry has proposed new concepts for wheels which are intended to lower rolling resistance until 2030 by 50%.

Aerodynamic resistance results from the product of aerodynamic drag (c_w) and frontal area (A). While there is a continuous decrease in c_w, A shows an increase. Regarding average European middle class vehicles, c_w has decreased from 0.35 in 1995 to 0.3 in 2006. Further potential is given by optimising car underside and engine air flow. A c_w of 0.2 seems in reach in the mid term (Schedel, 2007). Lowering of aerodynamic resistance by 10% is feasible at relative low cost. At constant driving at 120 km h^{-1}, this would lower fuel consumption by 20%.

5.2.2. Alternative drivetrains

Alternative drivetrains have in theory a higher potential to reduce GHG emissions than the options discussed above. Electric vehicles offer true zero carbon and air pollution emissions on the road. Battery- and fuel-cell electric vehicles are the most prominent alternatives to the internal combustion engine.

Battery-electric vehicles carry their energy along on-board in chemical form. However, the present nickel metal hydride (NiMH) batteries have the disadvantage of low energy density and high additional weight, clearly reducing the driving range. A NiMH battery allowing 100 km non-stop travel would weigh 340 kg (Van Mierlo et al., 2006) at high costs. More recent high-energy lithium-Ion batteries, which are still subject to safety concerns, reduce the weight to 180 kg (Van Mierlo et al., 2006) at even higher costs today.

Fuel-cell vehicles produce the electricity for propulsion by electrochemical reactions of hydrogen with oxygen. They have their energy stored on board in form of hydrogen or materials to produce hydrogen from. FCVs provide high efficiency for the production of electricity and locally zero emission driving. But they shift emissions to the hydrogen production, depending on the energy source (see also Section 5.3). Polymer electrolyte membrane fuel cells (PEMFC) are preferred for vehicle applications due to their high power density, which offers low weight, cost and volume (Neburchilov et al., 2007; Zhang et al., 2006). Average drive cycle efficiencies have reached 36% equivalent to 4.3 l Diesel/100 km (EDC) (von Helmolt and Eberle, 2007). Major problems to be addressed are durability with cycling of the fuel cell stack (status: 2000 h, target: 5000 h) (Budd, 2006), operating temperature range (status: −20 °C, target: −40 °C) and cost reductions (status: 120 \$ kWe^{-1}, target: 25–35 \$ kWe^{-1}) (DoE, 2007). Hydrogen onboard storage is a further critical issue to provide sufficient driving range. A target of hydrogen storage of 6 wt% on a system basis is generally considered hard to reach (Ross, 2006). Status today is 3–4 wt% (Chalk and Miller, 2006). Fuel cells can also be used for trains and ships.

5.2.3. High-speed rail

High-Speed Rail (HSR) is an opportunity to make land transport more competitive to air transport. It consists of rail technologies capable of speeds above 250 km h^{-1} and up to 400 km h^{-1}, travelling on new dedicated tracks. HSR offers time savings, additional capacity, reduced externalities and higher average load factors compared to conventional trains (De Rus and Nash, 2007). HSR can provide journey times competitive with air transport distances up to 650 km. Compared to passenger aircrafts, HSR's energy consumption is approximately 2–3 times more efficient. Differences in CO_2-emissions are even higher (factor 6–25) depending on the electricity mix used by HSR (Janic, 2003). However, HSR consumes more energy than lower speed trains and cars on motorways. Nevertheless, it is generally acknowledged that HSR emits less pollutants than airplanes and private cars (Campos and de Rus, 2009). The major disadvantage of HSR manifests in very high capital costs due to huge initial investments (De Rus and Nash, 2007).

5.3. Alternative fuels and lifecycle analysis

Alternative fuels constitute an option to lower GHG emissions apart from other motivations like lowering crude oil dependency, support of agriculture and local air pollution abatement. A considerable number of fuel options are suggested, characterised by varying carbon and hydrogen content and ranging up to zero carbon emissions at the time of energy conversion in the vehicle.

5.3.1. Natural gas (CNG, GTL)

Natural gas has about 20% lower CO_2-emissions per MJ fuel compared to gasoline due to its higher content of hydrogen. While until recently average NG fleet vehicles in Europe could save only up to 6% due to less well adopted engine technology (Umierski et al., 2004) more recent vehicles can save up to 19% despite of approx. 200 kg more weight.

Conversion of natural gas to synthetic fuels like synthetic Diesel, Methanol, Dimethyl ether or gasoline is another way to use it as an energy source for transport. This leads to very clean fuels, generally lowering air pollutant emissions, but does not contribute to a CO_2 reduction compared to the direct use of natural gas, as there is generally energy lost in the conversion step.

5.3.2. Renewable fuels from biomass and waste

Biofuels offer the benefit of a more or less balanced carbon cycle in contrast to fossil fuels. The CO_2 of biofuels emitted as they are burned, was absorbed from the atmosphere by the plants in a relative short period. However the production process lowers the net benefit, depending on feedstock, production means (e.g. fertilizers etc.) and conversion technologies used.

Today, bioethanol from sugar cane (Brazil) and corn (US) and biodiesel from rape seed and palm oil used in Europe are the dominant biofuels used in transport. Bioethanol is currently blended with gasoline, and biodiesel is blended with fossil diesel – both options are used in conventional ICE vehicles.

Bioethanol is produced from biomass which contains sugars or substances that can be converted into sugars such as starch or cellulose. GHG emissions are reduced today only moderately by about 13% (Farrell et al., 2006; US-context).

Biodiesel from oil seeds represents almost 80% of the liquid biofuel produced in Europe in 2006 (EurObserv'ER, 2007). Rape seed, and to a lower extent sunflower, palm oil and animal fat is used as feedstock. Since pure biodiesel use is not in agreement with emission regulations the trend is towards blending with conventional diesel up to 5% by volume (EN 590). Best estimate for net reduction in GHG emissions is 37% within a range of 10–66% (Edwards et al., 2007). The technology for more advanced, 2nd generation biodiesel with lower emissions is in the demonstration stage (WSDA, 2007).

Biomethane (Biogas) can be produced from a variety of biomass e.g. maize, cereals, sunflower, grass and waste by anaerobic digestion. Optimised methane yield from versatile crop rotations that integrate production of food, feed and energy, are possible (Amon et al., 2007). Biogas also makes decentralised production possible, which is energy efficient due to saved transports.

Major barriers for biofuels are higher costs, compatibility with conventional fuels and availability of technology for more advanced biofuels. Moreover, the combination of food, feed and fuel in one crop raises concern on influences of food production and prices, which could be observed already in the case of maize production in Mexico. Although land is available to some extent due to overproduction in some areas, the economic influence is still given. Therefore energy plants, which do not contribute to food production, seem to be better suited for fuel production. Second, in order to improve crop yield, genetic engineering is and will be applied. This however has met scepticism and regulatory hurdles in many countries (Torney et al., 2007). The use of biomass for heat and power generation leads generally to higher GHG reductions than the conversion to transport fuels. However, it has to be recognised that less options exist for liquid alternative fuels for the transport sector.

Although biofuels tend to show a positive effect on GHG emissions, several authors warn of hidden costs and adverse impacts on environment and society due to large scale production of biofuels (e.g. Palmer et al., 2007). Many important environmental effects of biofuels seem not well understood or taken into account, e.g. the influence of N_2O emissions (Crutzen et al., 2008). For state-of-the-art lifecycle analysis see e.g. Delucchi (2006) or Zah et al. (2007). An overview of net CO_2-eq emissions of alternative fuels is given in Fig. 19.

5.3.3. Hydrogen and electricity

Hydrogen (H_2) as an alternative energy carrier has the advantage that it can be produced from a wide variety of primary energy sources, fossil as well as renewable, e.g. wind, solar-thermal, photovoltaic, tidal/wave energy, geothermal, and biomass and waste. Today, most of the world's hydrogen is produced from natural gas. Hydrogen offers true zero emission at the tailpipe, if combined with fuel cells. If burned in internal combustion engines, only NO_x remains as significant air pollutant emission. Difficulties arise from the storage of hydrogen: energy density of gaseous hydrogen is low by volume, and in liquid form, very low temperatures are needed, which results in a lower overall efficiency and higher costs (Aceves et al., 2006). One of the main obstacles for the broad use of H_2 for transport is the lack of an adequate infrastructure for its distribution and the high costs for implementing it.

Electricity in battery-electric vehicles is recently discussed as a true alternative to hydrogen. This avoids the energy transformation cascade associate with the use of H_2. Advanced concepts of storing fluctuating renewable electricity in batteries of vehicles connected to the grid are under discussion, but the opportunities are not well assessed at the moment.

5.3.4. Life-cycle perspective

For the evaluation of the numerous technological options to mitigate greenhouse gas emissions of surface transport, the very complex, site dependent interrelations in ecology and economy have to be taken into account.

Life-cycle analysis (LCA), outlined in ISO 14040 et seq (2006), offers a methodology to address the potential environmental

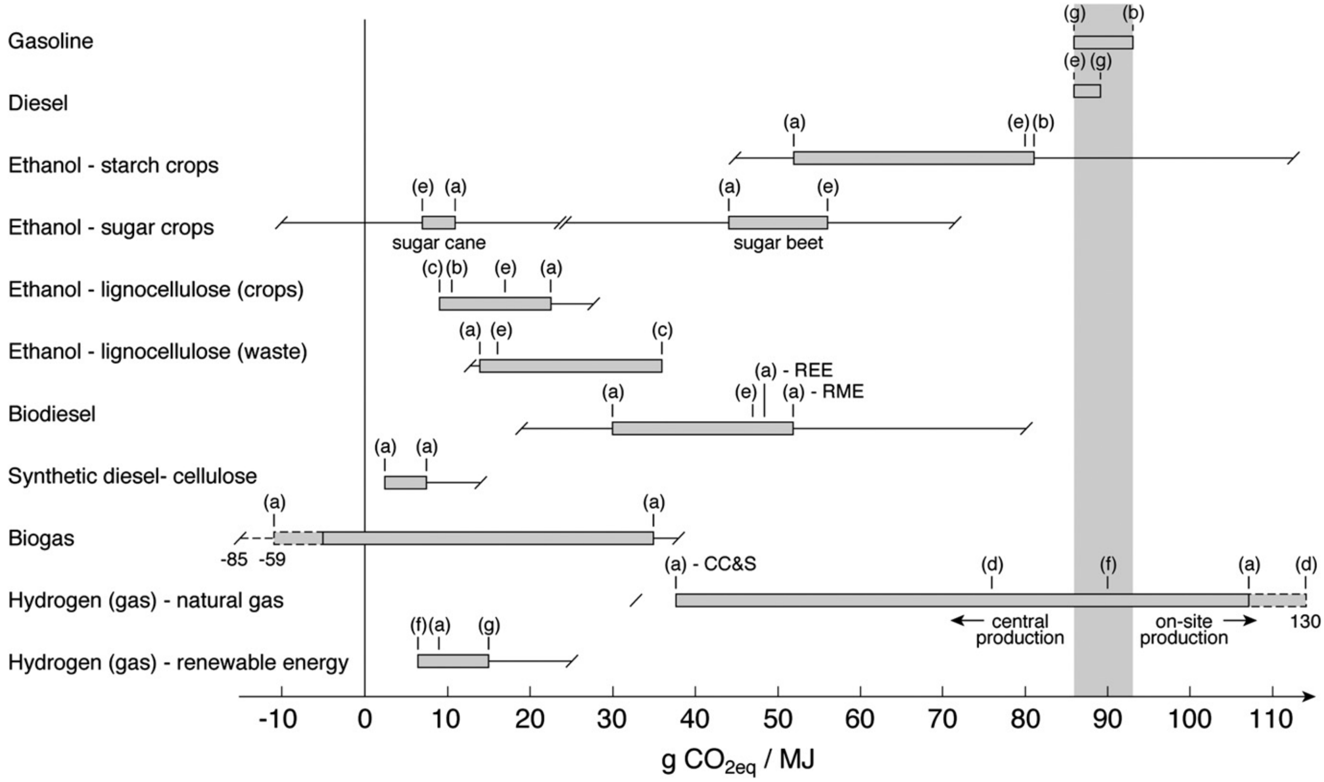

Fig. 19. Summary on net CO_2-eq emissions for some alternative fuels. Sources: (a) Edwards et al. (2007); (b) Farrell et al. (2006); (c) Kemppainen and Shonnard (2005); (d) MacLean and Lave (2003); (e) Ryan et al. (2006); (f) Wietschel et al. (2006); (g) Own calculations.

impacts throughout a product's life cycle in a consistent way. For transport, three life-cycle stages of the vehicle, 'upstream' (materials processing, parts assembly and distribution), 'on-the-road' operation, and 'downstream' (scrapping and disposal/recycling) plus the fuel cycle stages (extraction, processing and transport) have to be considered.

'Well-to-wheel' analysis describes an important part of a complete LCA, focusing only on propulsion system and fuel pathways. Several studies have been conducted for different geographic regions and time horizons e.g. by Edwards et al. (2007), Choudhury et al. (2002), Mizuho (2004), Schäfer et al. (2006) and Baba and Ishitani (2003). Exemplary results are presented in Fig. 20

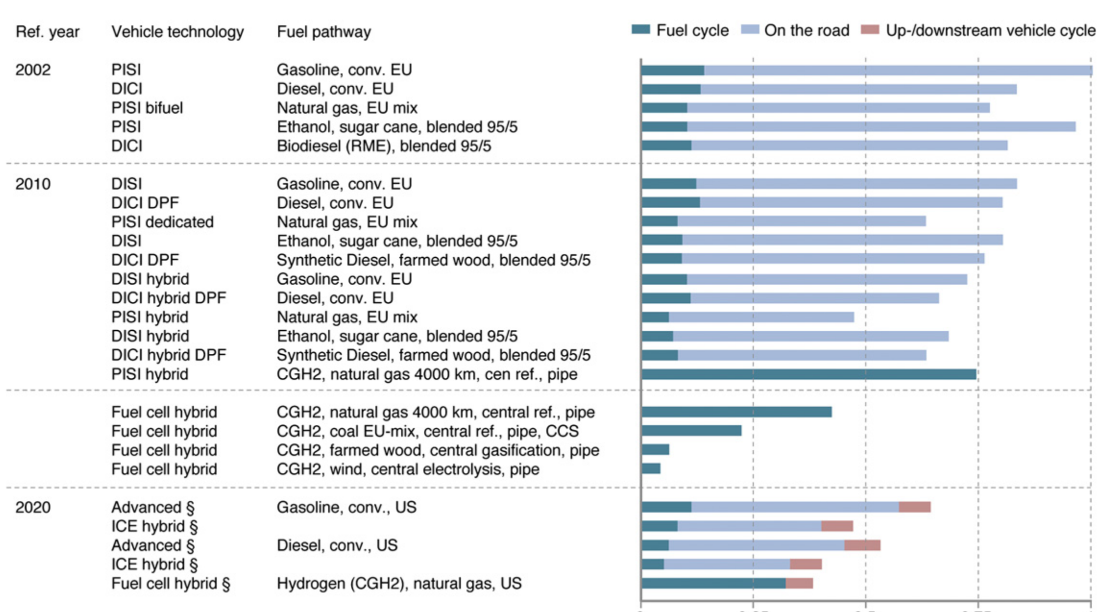

Fig. 20. Vehicle technologies and alternative fuels: CO_2-eq emissions well-to-wheels. Source § combined drive cycle US Urban 55%, US Highway 45%, normalised to 246 g CO_2 eq km^{-1}, data taken from (Schäfer et al., 2006), all other values refer to New European Drive Cycle (NEDC), normalised to 196 CO_2 eq km^{-1}, data taken from (Edwards et al., 2007). Figure composed by Stephan Schmid.

showing that potentially car technologies are conceivable which reduce CO_2-eq emissions by about 50%, on the long run even more. However for most technologies their economic viability on a large scale must still be proven.

Heavy goods road transport is less intensively assessed.

Problems of well-to-wheel studies limiting the validity and comparability of studies are uncertainty of data, differences in system boundaries and major differences in giving credits to by-products (Delucchi, 2006; Farrell et al., 2006). Up- and downstream processes for building and disposal of the vehicle are rarely taken into account. They become however more important with increase of lightweight design, the use of alternative powertrains and low-carbon fuels (Schäfer et al., 2006).

Despite given uncertainties we can conclude that generally more different fuels and more vehicle technologies are seen in the future concurrently.

5.4. Mobility management and policy option

5.4.1. Transport policy and environmental assessment

Transport regulation strategies in Europe, as expressed in the White Paper for European Transport policy (2001) aim at bringing about substantial improvements in the quality, sustainability and efficiency of transport. They also propose measures designed to gradually achieve a decoupling of constant transport increase and economic growth, in order to reduce the pressure on the environment. Major recommendations focussed on balancing modes of transport, eliminating bottlenecks, placing users at the heart of transport policy and on managing the globalisation of transport.

The strong growth of road transport compared to other land transport modes disables a correct exploitation of rail and shipping systems and, also, leads to the infrastructure saturation generating traffic congestion and pollution. To solve these problems the White Paper's action plan suggests measures aiming for the improvement of quality in the road sector, a revitalisation of the railways, a controlled growth in air transport, an adaption of the maritime and inland waterway transport system and a link between modes of transport. Placed into action, these measures have the potential to reduce significantly the number of road based transportation as demonstrated in Fig. 21.

To achieve a cohesive territory and a proper sustainable development, an interconnected European transport system, based on multi-modal corridors, high-speed passenger networks and improved traffic conditions, is needed. At the same time, roads must be safer, the transport costs should be transparent, intermodal transport systems must be implemented, the rights and obligation of users should be clearly defined and urban transports should be used in a rational way. As an example, infrastructures should be taxed considering its real direct and indirect costs, including externalities, i.e. indirect consequences for third parties, often for public goods. One of the goals is usually to reduce road transport with its larger harmful externalities especially in the freight sector. Table 16 shows the cost levels generated by a heavy goods vehicle covering 100 km on a motorway in open country at off-peak times. Estimates are made for the costs of air pollution (cost to health and damaged crops), climate change (floods and

Table 16
External and infrastructure costs of heavy goods vehicle travelling 100 km on a motorway with little traffic in Euro.

External and infrastructure costs	Average range [EUR]
Air pollution	2.3–15
Climate change	0.2–1.54
Infrastructure	2.1–3.3
Noise	0.7–4
Accidents	0.2–2.6
Congestion	2.7–9.3
Total	8–36

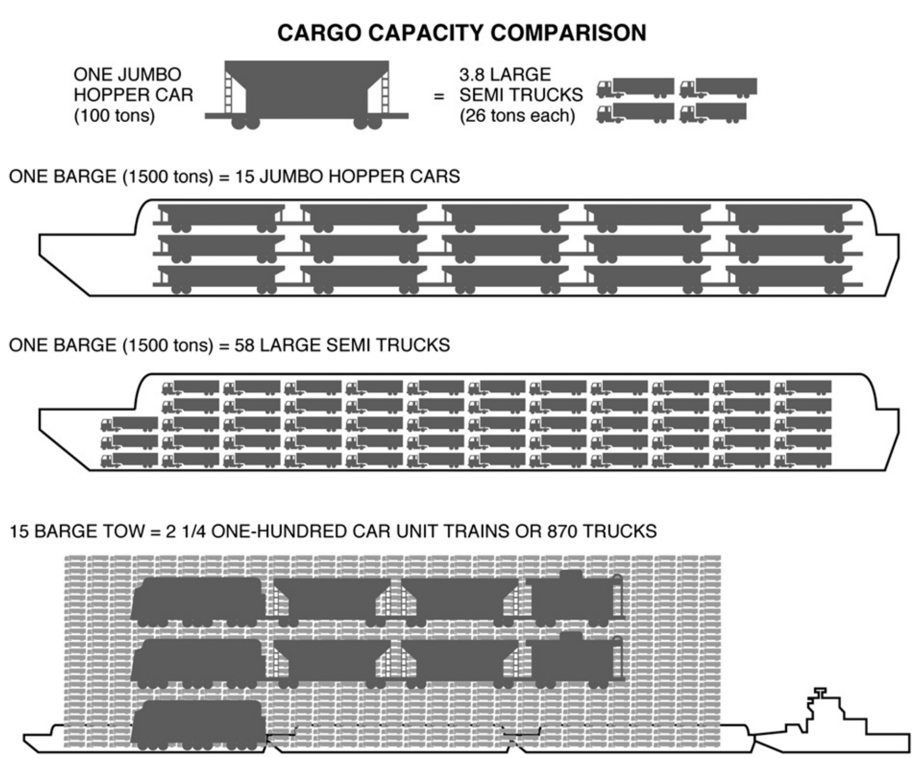

Fig. 21. Cargo capacity comparison. Figure by G. Feyerherd based on www.ccpa-ohioriver.com.

damaged crops), infrastructure, noise (cost to health), accidents (medical costs) and congestion (loss of time).

The management of transport globalisation faces a challenge since a large part of transport systems are regulated at international levels. These regulations are implemented to ensure easy trades and commerce overlooking, in many cases, issues related to the environment. To invert this tendency, measures promoting proper funding for well planned infrastructures, efficient alternative transport systems (railway and shipping) and the usage of new technologies not only in vehicles, but also in infrastructures and infrastructure planning, are needed.

The contribution of the Strategic Environmental Assessment (SEA), stated by Directive 2001/42/EC, should also be considered due to its potential to reduce transport emissions and their impact on air quality and climate change. In transport, SEA is particularly useful in assisting decisions on a multi-modal approach, comparing alternative planning and management options in an integrated way and providing decision-makers with the relevant information to enable them to take the most sustainable decision (European Commission, 1999). The most updated guidance document specific for the transport sector (European Commission, 2005a) is based on the results of the BEACON project (Beacon, final report 2005). The integration of SEA in transport planning was also a major issue of COST 350 (2006). An example of SEA applied to Portuguese High-Speed Rail Network demonstrate that, despite its higher investment when comparing with the traditional railway, it has positive effects such as the decrease of externalities related to accidents, climate change and air quality.

5.4.2. Land use and transport planning

Two important elements required for the reduction of transport emission have been discussed in Sections 5.2 and 5.3: vehicle technology and fuel properties. Land use planning, related to the numbers of kilometres travelled, is another essential tool due to its impact on transport demand, particularly for road traffic.

An integration of land use and transport planning is a key issue to reduce negative environmental impacts from transportation. For example, sprawling of urban areas creates an inefficient land use pattern, generates traffic and often disables public transport systems. Better community planning and more compact development help people live within walking or bicycling distance of some of the destinations they need to get to everyday such as work, shops, schools. If they choose to use a car, trips are short. One of the consequences of urban sprawl, intimately related with atmospheric emissions and air quality, is the growing consumption of energy. Fig. 22 presents data from a number of world cities, revealing that there is a consistent link between population density and energy consumption: high-energy consumption rates are associated with lower population densities, characteristic of sprawling urban environments. Increased energy consumption is in turn leading to the increase of CO_2 emissions to the atmosphere.

Fig. 23 presents the relationship between CO_2 emissions and population density for several European cities. It seems that emissions decrease progressively with the increase of urban densities, although not as evidently as in the case of energy consumption, revealing that other factors such as climate, fuel mix and industry activity are probably more important. A study (Borrego et al., 2006) investigated the effects of different city structures in air quality through the application of dispersion and photochemical models. In this study, in order to nullify the effects from local meteorology and other uncontrolled variables, three cities with distinct urban structures – dispersed, corridor and compact – were idealised. Result shows that the disperse city has the lowest emissions per area and the compact city has the lowest absolute emissions.

Research conducted by the UK government has suggested that spatial planning policies could reduce projected transport emissions by 16% over a 20-year period (European Sustainable Cities, 1996). Recent research published by the US Urban Land Institute (Ewing et al., 2007) identify compact city development with mixed uses (housing, commercial and industrial developments) as the best way in land pattern changes to reduce vehicle greenhouse gas emissions. It is reported that compact development may reduce the need to drive between 20% and 40% and reduce total transportation-related CO_2 emissions from current trends by 7–10% as of 2050.

The complexity of the interaction between transport and land-use makes it difficult to find how the system affects human behaviour. The TRANSLAND study has concluded that land-use and transport policies are only successful with respect to reduction of travel distances and travel time and reduction of share of car travel if they make car travel less attractive, i.e. more expensive or slower. On the other hand, transport policies to improve the attractiveness of public transport have in general not led to a major reduction of car travel (TRANSLAND, 2000).

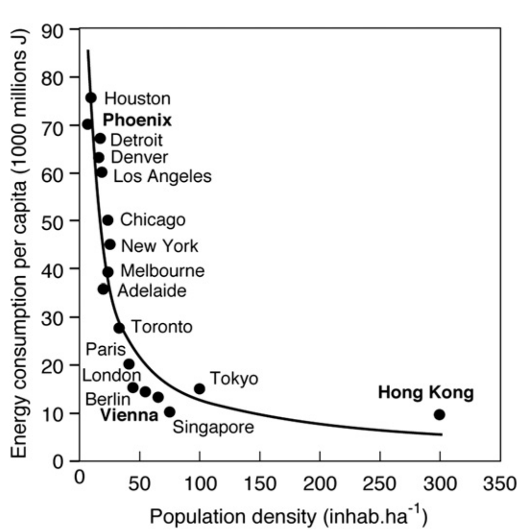

Fig. 22. Energy consumption per capita and population density for several world cities (adapted from Newman and Kenworthy, 1999).

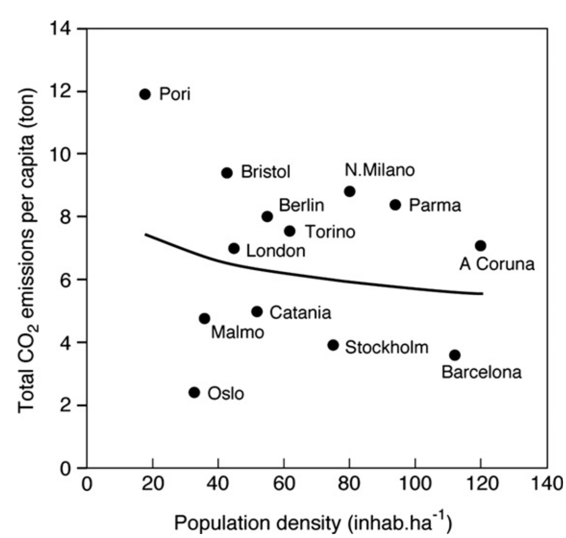

Fig. 23. CO_2 emissions per capita and population density for several world cities (adapted from Tarzia, 2003).

5.4.3. Mobility management

Mobility management aiming to influence travel choice by encouraging changes in behaviour on the part of organisations and individual travellers is one of the strategies to reduce the amount of road traffic. The desired behavioural changes include more efficient use of vehicles, for example through higher vehicle occupancies or less empty running, a switch to more sustainable transport modes and even increasing teleworking to reduce daily travels where appropriate. Mobility management is so far mainly being applied in a local and regional context focusing on the everyday mobility, especially commuting to work or to school (European Commission, 2004). The benefits of promotion range about a 10–20% decrease in car travel (MOST project, 2003).

The "Sustainable urban Transportation" project (SUTRA, 2003) developed a consistent and comprehensive approach and planning methodology for the analysis of urban transportation problems that helps to design strategies for sustainable cities. Combining an indicator based approach with simulation models and scenario analysis, socio-economic and environmental impact assessment, and a public information component, SUTRA includes awareness building and educational aspects for citizens and stake-holders participating in urban decision making processes. The effects of the measures included in the scenario definitions demonstrate that no single measure can have a dramatic effects by itself. Only the combination of mobility management and transport planning measures can lead to significant effects.

Although transport problems are well identified and their solutions are also known and accepted, there is a lack of action on implementation. Most action plans are still at the pilot stage and are locally applied. Although a precautionary approach is needed in order to avoid negative side effects, e.g. due to increased exposure to air pollution in compact cities, the full implementation of stated policies and measures at regional, supranational and even international scale is expected to have a strong impact on emission reduction and will contribute to the mitigation of transport impacts on climate and ozone.

The Section 5.4 was written in close cooperation by Prof. Carlos Borrego, Prof. Myriam Lopes and Dr. Oxana Tchepel at University of Aveiro, Portugal. The lead authors would like to express their thanks for this contribution to the Land Transport Assessment.

5.5. Scenarios of future road transport exhaust emissions

Scenarios for road transport on the global or supranational level have mostly focussed on fuel demand and related CO_2 emissions. Very few scenarios incorporate exhaust emissions as well. Of course, they differ in their assumptions, the degree of detail, the input data and their treatment, etc. according to the purpose they have been designed for. The purpose of relevant road transport emission scenarios can be classified as follows:

a) Scenarios that investigate the impact of policies implemented up to a certain point in time, sometimes called *frozen policy, current legislation or do-nothing scenarios*. They may serve to illustrate the outcome of autonomous developments without any further (external) action, measure or policy. Often they are used as the backdrop when illustrating the impact of measures that have been, will be or could have been taken. The "International Energy Outlook" is an example for such a scenario type (US-DoE, 2006).
b) Some scenarios assume the continuation of certain trends observed in the past, in addition to very likely policies or measures to be implemented in the foreseeable future above and on top of all policies or measures that have already been implemented. Scenarios of this kind are often called *trend, forecast or business-as-usual scenarios*. Examples reviewed here include the 'Reference' or 'Baseline' scenarios of Fulton and Eads (2004), IEA (2006), Turton (2006), European Commission (2004), and a road scenario of the IPCC SRES B2-type presented here for the first time (Borken-Kleefeld et al., in preparation).
c) Some scenarios intend to analyse the consequences of dedicated policies that have not necessarily yet been scheduled for implementation, of technologies still under development or of other changes yet to be seen. This kind may be termed *policy scenarios* as they usually require an active change from past practise. Examples reviewed here include the ACT and TechPlus scenarios of IEA (2006), and the road scenarios of the IPCC SRES A1B-, A2- and B2-types presented here for the first time (Borken-Kleefeld et al., in preparation).

All these three scenarios are forecasting scenarios: The analysis starts from a given (historic) year and produces – in our case – likely, possible or feasible future fuel consumption and emission estimates as a function of the driving forces modelled. Thus the future results are open and not prescribed per se.

d) *Backcasting scenarios* take a different approach: The future state is prescribed e.g. in terms of energy consumption or emissions; the necessary developments are then determined inversely. Such scenarios are used to analyse possible pathways and required changes in structures, behaviour and technologies that typically go far beyond business-as-usual assumptions in order to arrive at a desired target state. The example reviewed here is the "Energy Revolution" scenario (Greenpeace/EREC, 2008; Krewitt et al., 2009).

It is important to keep in mind that scenarios are not predictions of the future (compare Grunwald, 2002). Scenarios rather summarize the *current knowledge and expectations* about possible future developments. Therefore, scenarios may differ in the analysis what interaction are important and in the assumed future development of the main driving forces. Different scenarios from one of the four classes listed above can inform about different knowledge, interpretation or indeed uncertainty in input data, future assumptions, concepts and relationships, etc. which all claim to apply to the same subject. Scenarios of different classes represent more variability and their modelled differences are at least partly due to a different approach and input data. Nonetheless, in the best cases they serve to analyse the consequences of certain policies or measures, in particular relative to the incremental difference in assumptions. Table 17 summarises important characteristics of scenarios on road transport's long-term fuel consumption (and sometimes exhaust emissions) to be considered in the following.

5.5.1. Global CO_2 emission scenarios for road transportation

5.5.1.1. Forecasting scenarios. There are only few global scenarios for road transportation and most focus on the fuel demand. We review global exhaust emissions first and then analyse regional differences (Fig. 24).

The US Energy Information Administration has published its International Energy Outlook annually. The future global fuel supply and demand is projected under "frozen policy" assumption. For the version 2006 refereed here (US-DoE, 2006) policies that have not been enacted by 2006 are not considered. No autonomous trends are assumed; new technologies are only taken into account if they are either legislated or cost-effective from *a private consumer perspective*, i.e. paying back an extra investment within up to 3 years (John Maples, US-EIA, pers. comm. 6 May 2009). Under these

Table 17
Summary of scenario characteristics relevant for road transport's long-term fuel consumption and/or exhaust emissions.

Type	'Original name' and scenario characteristics
International Energy Outlook 2006 (US-DoE, 2006)	
Frozen GDP sensitivity	'Reference': Policies enacted by Jan. 2006; 'High/Low economy': Variation of Reference scenario with higher/lower growth rates of GDP
Sustainable Mobility 2030 Project (Fulton and Eads, 2004)	
Frozen	'Reference': Policies enacted by 2003 + policy trajectories: Same energy intensity developments as IEA's WEO 2002 'Reference Case', but about 10% higher transport activity, for both passenger and freight transport. (Further tightening of veh. exhaust em. standards in developing countries; no further reduction in LDV fuel economy. Otherwise historic trends and extrapolation from 2030 to 2050.)
Energy Technology Perspectives 2050 (IEA, 2006)	
Trend	'Baseline': Equal to 'reference scenario' of the World Energy Outlook 2005, but extended from 2030 to 2050. Calculates effects of technology developments of policies already enacted
Policy	'Accelerated Policy Scenario ACT Map'; Analysis the impact of technologies and best practices aimed "at reducing energy demand and emissions, and diversifying energy sources. The focus is on technologies which exist today or are likely to become commercially available in the next two decades"
Policy	'TECH Plus'; As above, but "more optimistic assumptions" about the rate of technological improvements
Quantify Road scenarios (Borken-Kleefeld et al., 2008)	
Policy	A1B: Interpretation of the IPCC SRES 2000 storyline A1B. GDP and population projections taken from marker scenario. Own assumptions/derivation of passenger and freight transport volume, vehicle efficiency improvements, exhaust emission control, fuel shares. Transport volumes and road transport's energy consumption calibrated to y2000 levels
Policy	A2: Interpretation of the IPCC SRES 2000 storyline A2. Approach as above
Policy	B1: Interpretation of the IPCC SRES 2000 storyline B1. Approach as above
Policy	B2: Interpretation of the IPCC SRES 2000 storyline B2. Approach as above
(Turton, 2006)	
Policy	B2 transportation scenario: Own interpretation of SRES 2000 B2 marker scenario (Riahi and Roehrl, 2000); GDP and energy consumption calibrated to y2000 values, updated population projections. Car travel demand modelled from time-money budgets based on Schafer (2000); autonomous efficiency improvements for car of 2% per decade. Road freight transport energy demand scaled from 2000 levels with general transport energy development of original B2 scenario (Riahi and Roehrl, 2000)
European Energy and Transport Scenarios (European Commission, 2004)	
Frozen	'Baseline': Policies enacted or in implementation by end 2001. Including effects from the VA with ACEA/JAMA/KAMA on reduction of passenger car fuel consumption. Excluding policy forced implementation of Biofuels Directive
Policy	'High-efficiency and renewables' ⇔ 'Energy policy': Active policies to promote higher vehicle fuel efficiency and full compliance with Biofuels Directive
Policy	'Promoting rail and higher load factors': Active policy to increase modal share of rail and public road transport and higher capacity utilisation – corresponding to an implementation of the Transport White Paper Scenario C by 2010
Policy	'Extended policy options' ⇔ 'Full policy options': Active policy combining the above scenarios 'High-efficiency and renewables' and 'Promoting rail and higher load factors', in other words: A full implementation of the Biofuels Directive and of the Transport White Paper Scenario C by 2010

assumptions the global fuel demand of the transport sector is expected to increase by about 50% over the period 2000–2030. This forecast has hardly changed for the most recent 2009 version (US-DoE, 2009). Average growth rates in non-OECD countries are projected at about 2.3% per year, almost a factor 3 higher than in OECD countries (0.8% p.a.); given the differing absolute consumption level, non-OECD countries account for about two thirds of total demand increase, accounting in 2030 for more than 40% of total global fuel demand in the transport sector. The EIA does not assume an increase in biofuels in the transport sector. Therefore global CO_2 emissions from transportation are expected to grow at the same rate as fuel demand in the period.

Fulton and Eads (2004) projected fuel consumption and exhaust emissions from transportation globally in work for a group of automobile manufacturers, suppliers and oil companies. The future developments of vehicle mileage, fuel efficiency and exhaust emission control are modelled from past trends. Developing countries are assumed to gradually adopt as stringent exhaust emission standards as industrialised countries. Data quality is considered good for OECD countries, but mostly poor for developing countries. In fact, in the so-called 'Reference Case' the same assumptions are made e.g. for vehicle mileage, emission factors, fuel and vehicle shares, change rates etc. for all developing regions together without differentiation. The 'Reference Scenario' can be classified as a business-as-usual scenario. Under these assumptions, global road passenger travel is calculated to increase by 40% and 90% in 2030 and 2050 respectively, while road freight transport increases by 125% and 240% in the same period. Transport volumes grow and remain high in OECD regions, but highest growth rates are assumed for developing countries. With assumed autonomous vehicle efficiency improvements fuel consumption and CO_2 emissions from road transportation are calculated to increase from the year 2000 level by 64% and 118% until 2030 and 2050 respectively. In the same period the assumed further tightening of vehicle exhaust emission standards throughout all world regions results in a continuous decline of exhaust emission of NO_x, VOC, CO and PM down by −70% in 2030 and −90% in 2050, relative to the year 2000 level each. Non-fossil fuels are assumed to account for less than 2% of global road transport fuel consumption. Central for the results are assumed improvements in efficiency and exhaust emission controls.

The International Energy Agency has published Energy Technology Perspectives 2050 (ETP) (IEA, 2006, 2008b). A business-as-usual scenario, based on the Agency's World Energy Outlook (IEA, 2008a) is developed for 2050. This 'Reference Scenario' serves as background to two active policy scenarios. These are designed to analyse how much fuel consumption and CO_2 emissions could be reduced under optimistic assumptions about technological progress and about dedicated policies. Data are only given for the total transport sector; road transport accounted for about 80% of total demand. The 2008 version of Energy Technology Perspectives 2050 (IEA, 2008b) reflects increased policy attention to fuel savings and

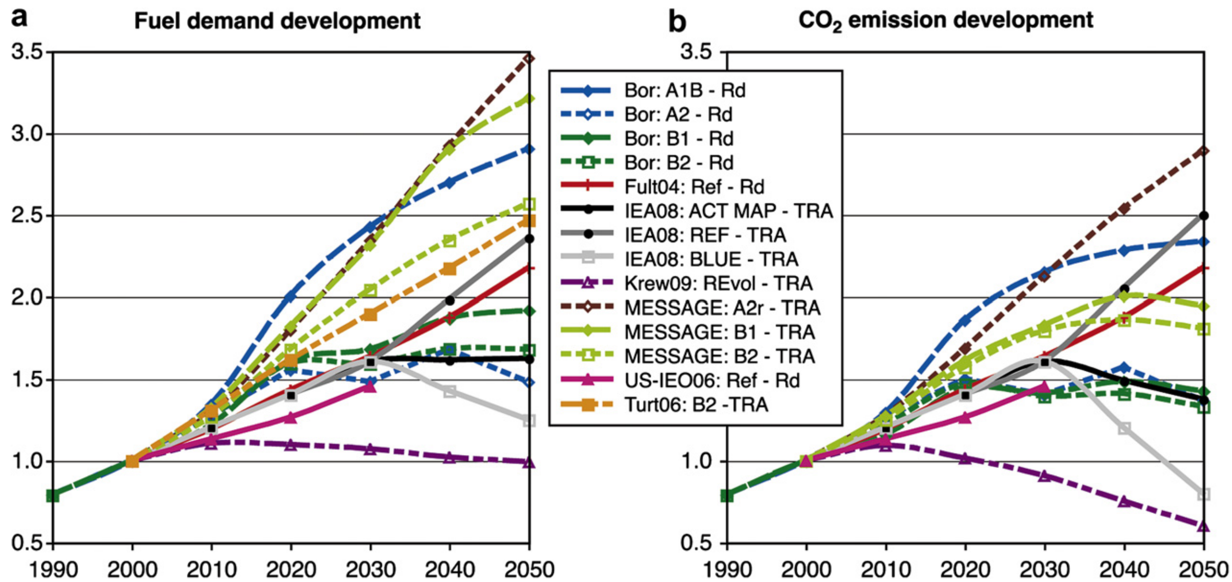

Fig. 24. Scenarios for global (road) transport for a) fuel demand and b) CO_2 emissions from 1990 to 2050, relative to the year 2000. Solid lines designate the IEA scenario family, dashed lines designate IPCC SRES type scenarios. Scenarios are identified by author, scenario abbreviation and Rd/TRA, when data are for road transport or for the whole transport sector. Bor = Borken-Kleefeld et al.; Fult04 = Fulton and Eads, 2004; IEA008 = IEA, 2008b; Krew09 = Krewitt et al., 2009; MESSAGE = IIASA-GGI, 2007; US-IEO06 = US-DoE, 2006; Turt06 = Turton, 2006.

carbon emissions, progress on conventional vehicles' fuel efficiency and the potential electrification of the road transport. Global transport fuel demand is projected to increase by more than 60% and about 140% until 2030 and 2050 respectively from the level in the year 2000. The projected increase in the business-as-usual case is about 5% up from the previous estimate (IEA, 2006) and somewhat higher than estimated by Fulton and Eads (2004).

Most would be supplied from oil, with liquified coal or gas providing 22% and biofuels only 3% in 2050. 2nd generation biofuels would not have become commercially viable. The resulting CO_2 emissions, including upstream emission for the provision of the different fuels, are projected at 18 Gt, about 150% above the emissions in the year 2000. This increase could be reduced if technologies and policies are actively pursued to reduced and diversify energy demand, according to IEA (2008b): Two policy scenarios analysed the impact of much higher improvements of the vehicles fuel efficiencies and of a strong decrease of prices for biofuels and renewable hydrogen in the transport sector in the period 2030–2050. Transport demand remained as in the 'Reference Scenario'.

The 2008 version of the Accelerated Technology Scenario (ACT Map) calculates the impact if technologies were applied that are economical at a carbon charge of up to US$ 50 per tonne CO_2 avoided. This could stimulate development and deployment of a light-duty vehicle fleet that is 50% more efficient than in 2005, compared to 20% efficiency improvement according to the baseline scenario. This would reflect a maximum use of fuel efficient technologies for conventional gasoline and diesel cars, a dieselization of the fleet, a lower growth of light trucks, vans and SUVs, and a dominance of hybrid vehicle concepts by 2050. About one quarter of the vehicles could be plug-in hybrids running half the time on grid electricity. Truck efficiency improvements could grow in the same period to 35%, compared to 25% improvement in the baseline. 2nd generation biofuels would increase under these assumptions to a share of 17%, more than a factor 5 increase relative to the baseline projection. Low-GHG electricity could provide about 2% of the final energy demand. Fossil synfuels would not be used in this scenario. Under these assumptions, total fuel demand could be 30% lower than in the business-as-usual projection for 2050, but still more than 65% higher than in 2000. Together with the substitution of synfuels by low-GHG biofuels (and electricity) total CO_2 emissions could be 45% lower than the projected baseline in 2050.

In the BLUE map scenario more speculative breakthroughs in either fuel cell or battery technology are assumed. Then more hydrogen, plug-in hybrid or battery-electric vehicles could be deployed. These vehicles offer the double advantage of a significantly higher fuel efficiency and low-carbon energy (provided the hydrogen or electricity is produced from low-carbon primary fuels). This might reduce global transport fuel demand by 47% and reduce the related CO_2 emissions by more than 67%, each below the projected 2050 baseline.

5.5.1.2. Policy scenarios. IPCC's Special Report on Emission Scenarios (Nakicenovic et al., 2000) developed a set of global scenarios of GDP and population long-term developments, along with four qualitative storylines about the development of efficiencies and primary energy supply. Key assumptions for the four scenario storylines are summarised in Table 18. Broadly speaking, scenarios A1B and A2 put more emphasis on economic growth, while scenarios B1 and B2 assume a reduction in consumption and a higher environmental awareness. Fuel efficiency improvements are high to very high in scenarios A1B and B1, moderate in scenario B2 and low in scenario A2. The share of low-carbon fuels is assumed high in B1 and B2, medium to high in A1B and low in A2. No dedicated climate mitigation measures are assumed. By many B2 is considered as a business-as-usual scenario, while B1 is considered as an environmentally oriented policy scenario, A2 as a laissez-faire non-globalised market oriented scenario and A1B as a globalised, market oriented high growth scenario. Note, that Nakicenovic et al. (2000) assume a significantly higher growth in GDP than the more recent IEA outlooks. Thus, transport and fuel demand are already above the IEA projections.

Table 18
Key assumptions for the different IPCC emission scenario families (Nakicenovic et al., 2000).

Scenario family	A1B – 'Global economy'	A2 – 'Fragmented economy'	B1 – 'Global ecology'	B2 – 'Fragmented trend'
Population growth	Low	Low	Low	Medium
GDP growth	Very rapid	Medium	High	Medium
Energy use	Very high	High	Low	Medium
Oil and gas availability	Medium (=exploitation of non-conventional oil)	Low	Low (=peak and decline)	Medium
Pace of energy/oil & gas exploitation	Rapidly new + More efficient technologies	Slow	Rapidly clean + resource effic.	Medium
Oil & gas exploitation favouring	Balanced with other energy sources	Regional	Efficiency & dematerialisation	"Dynamics as usual"
Philosophy	Convergence + Interactions between regions. (Global Economy, high growth & technology)	Self-reliance, local/regional identities	Service + Information economy. Dematerialisation (Global Ecology, growth, efficiency and biofuels)	Local/regional solutions on economic, social, environm. Issues

Here we discuss the emission projections for the whole transport sector[2] for IPCC scenario families B1, B2 and A2r[3], as calculated with the MESSAGE model (Riahi et al., 2006; IIASA-GGI, 2007; Riahi, personal communication, 17 Jan 2008). The B2 scenario is interpreted as a business-as-usual scenario. Global fuel demand is assumed to grow by more than 100% from 2000 until 2030 and by almost 160% until 2050 respectively. The growth rates calculated by Turton (2006) for this scenario, also using the MESSAGE model, are comparable: +90% until 2030 and +150% until 2050 for all transportation globally. Both arrive at thus at 15–20% higher transport fuel demand in 2050 than the Energy Technology Perspectives (IEA, 2008b) reviewed above. Transport's CO_2 emissions grow less and even stagnate at +80% above the year 2000 level between 2030 and 2050 as biofuels are assumed to be phased in. In 2030 and 2050 their share is 10% and 23% respectively. Furthermore, the supply gap resulting from declining oil reserves is covered by synfuels derived from natural gas or coal. Their shares grows continuously to 6% and 14% in 2030 and 2050. However, in stark contrast to the expectations in the Energy Technology Perspectives of IEA (2008b), their production is assumed to be coupled with carbon capture and storage (CCS), so upstream CO_2 emissions are limited. Therefore, the emission growth is almost a factor of 2 lower than in IEA (2008b). Hydrogen and electricity are assumed to have less than 5% share in 2050, in line with the assumptions of the 2006 version of the ETP 2050 (IEA, 2006), but more than in the most recent 'Perspectives' (IEA, 2008b).

The laissez-faire scenario A2r calculated a much higher growth in fuel demand: Relative to 2000 transportation fuel demand grows by 130% and 250% until 2030 and 2050 respectively. As much less biofuels or CCS are used, CO_2 emissions grow in the same periods by 110% and 190%, respectively. Illustrating the effects of policy, the 'global ecology' scenario B1 is assumed to have almost twice as high GDP growth as scenario A2r until 2050 but also assumes dedicated improvements in fuel efficiency and decarbonisation globally. Hence with slightly lower growth rates for the fuel demand than A2r the resulting CO_2 emissions grow only by 80% and 95% until 2030 and 2050 respectively. A strong decarbonisation of the transport fuel is assumed to set in from 2030 onwards. Though only few details are given the key developments are efficiency improvements and low-carbon fuels, partly the result of an assumed widespread application of carbon capture and storage.

Genuine transport interpretations of these same storylines (Nakicenovic et al., 2000) were developed within the *Quantify* project; they are presented here for the first time (cf. Borken-Kleefeld et al., 2008 for details on the base year 2000; Borken-Kleefeld et al., forthcoming). The assumed developments for population and GDP are taken over from the respective marker scenarios, and transport demand is derived for twelve world regions separately. No dedicated climate mitigation measures are assumed. But current policy trends (as off end 2007) are continued into the future, notably as concerns the introduction and further tightening of exhaust emission standards in more and more world regions; this is important for the non-CO_2 emissions. According to these scenarios, fuel demand for road transportation is going to increase strongly over the next decades, but always much less than in the respective MESSAGE scenario: In the case of high economic growth (A1B: increase by factor 6.7), fuel demand in 2050 may be 190% higher than in 2000, about 50% higher than projections by the IEA (2006, 2008b). Biofuels as well as gas- and coal-derived synfuels could provide 13% each in 2050, totalling more than 500 Mtoe. Low-carbon electricity or hydrogen might achieve 5% supply share, if this technology was pushed. Consequently CO_2 emissions grow in scenario A1B by about 130% from 2000 to 2050, significantly less than fuel demand. This growth corresponds to the projections in the ETP reports (IEA, 2006, 2008b). If fuel efficiency policies were more aggressively pursued, as assumed in scenario B1, fuel demand might only grow by 90% from 2000 to 2050, with global GDP growing by a factor of 4.8 over the same period. This is about 50% lower than the trend projections by the IEA (2006, 2008b). About 20% of the demand could be covered by – mostly 2nd generation – biofuels, policy support provided. This assumption corresponds to the ACT Map scenario (IEA, 2008b). Low-carbon electricity or hydrogen could reach 4% supply share in 2050, mostly assumed in urban light-duty travel. Consequently fossil CO_2 emissions could be grow only by 43% until 2050. With efficiency policies and restraint in transport demand, the overall fuel demand could grow only by 68% until 2050, when GDP grows by a factor 4.1 (scenario B2). With the development of 2nd generation biofuels given priority, about 20% of the fuel demand could be covered in 2050. Then growth in fossil CO_2 emissions could be as low as 33%.

Without efficiency polices, as in scenario A2, fuel demand could still grow by 48% when global GDP is estimated to be a factor 2.7 higher in 2050. Without development of new energy carriers or reduction of carbon emissions petroleum might supply 86% of the fuel, 8% by fossil synfuels and 5% by 1st generation biofuels. This would be the most CO_2-intensive energy supply and CO_2 emissions grow roughly in line with fuel demand growth (+37%), only slightly reduced by a dieselization of the light-duty fleet.

5.5.1.3. Backcasting scenarios. A different perspective is provided by the Energy [R]evolution scenario developed by Greenpeace and the European Renewable Energy Council (Greenpeace/EREC, 2008; Krewitt et al., 2009). This is a backcasting scenario designed to

[2] Again, we can assume that 80% of total transport fuel demand is for road transportation in 2000.
[3] A2r is a revised version of the original A2 scenario.

illustrate a possible pathway how to reduce global CO_2 emissions by 60% compared to 2005, with emissions from the transport sector to be *reduced* by 40% over this period. This contrasts strongly with all forecasting results discussed above: All but one, the speculative ETP 2008 BLUE Map scenario (IEA, 2008b), calculate an *increase* of CO_2 emissions of at least 30% in that period. Hence, a very aggressive efficiency improvements as well as significant trend breaks in behaviour must be assumed in order to achieve the significant cuts in road transport's CO_2 emissions (Greenpeace/EREC, 2008):

- Growth in passenger and freight transport demand must be contained in order to achieve the CO_2 target. Passenger transport demand per capita is assumed to be even 10% less in the OECD regions in 2050 compared to the Reference Scenario[4]. Through improved logistics, the growth in road freight transport is assumed to be 5% less than in the Reference Scenario, taken from Fulton and Eads (2004).
- Furthermore, road transport needs to be shifted to a (much improved) rail. It is assumed that about 7.5% of car travel can be shifted to bus and rail, which in turn are assumed to be 70% and 80% respectively more energy efficient. Consequently, total car travel grows only by 120 % from 2005 to 2050, compared to 200% in the Reference Scenario. For trucking, the authors assume that 5% and 2.5% of medium and heavy-duty truck transport can shifted to rail.
- The vehicle fuel efficiency for all, cars, light, medium and heavy trucks, and buses must increase twice as much as under trend assumptions. This is aided by an aggressive hybridisation and electrification of vehicles. The fuel efficiency of light-duty vehicles needs to be increased by a factor 4 from 10 l_{ge}/100 km in 2005–2.5 l_{ge}/100 km in 2050. This is still a factor 2 lower than trend projections in the Reference Scenario for 2050. According to the authors, this might be achieved by a significant downsizing and about 30% less vehicle weight, 20–25% improvement of the conventional diesel and gasoline powertrains, about one third of dedicated full hybrid vehicles, more than one third battery-electric and plug-in hybrid vehicles with up to 80% grid electric drive, an reduction of auxiliary, aerodynamic and friction losses by 50% as well as a significant shift to smaller vehicles in general (Schmid, 2009).

  The fuel efficiency of trucks (measured in MJ per tonne-km) needs to increase by more than a factor of 2 until 2050 relative to 2005. This is another 45% below the already improved value in the Reference Scenario for 2050.

If these measures were implemented then transport fuel demand would grow only little and could decline from 2040 onwards to the year 2000 level.

- The remaining CO_2 reduction gap is covered by a 36% share of renewable energy in final energy demand of the transport sector. This is supplied by about 300 Mtoe biofuels and 370 Mtoe renewable electricity; together this is almost a factor 5 more renewable energy supply than the 2050 value in the Reference Scenario, but much less than in the most optimistic ETP 2050 BLUE Map scenario (IEA, 2008b). Renewable hydrogen does not play a major role in 2050 principally due to the high costs for the build-up of the supply infrastructure; furthermore fuel-cell vehicles are assumed to offer only little efficiency advantage over plug-in hybrids.

Only when all these factors together are achieved then a reduction of transport's CO_2 emissions by 40% below the year 2000 level might be achievable. A dedicated, consistent and long-term policy and major investments are needed. Major technological advances must be matched with a trend break in consumer behaviour: Lower passenger and freight transport demand and a decided preference for smaller, possibly less performing but also less consuming conventional, hybrid and electric vehicles. But even in this most ambitious (and speculative) scenario the potential CO_2 emission reductions in the transport sector will be below the average (or the required) reductions of other parts of the economy/society. If this is so, then other sectors will have to reduce beyond average to cover up the required emission reduction.

In all scenarios much of the growth results from developing regions, notably in Asia, while emissions form industrialised countries often remain at high levels. This is because in the OECD, the dynamics is lower while developing regions have a broader span of potential pathways. We illustrate these differences by the example of emission scenarios for Europe (Western, Central and Eastern) and developing Asia (i.e. excluding Japan and Korea) in Fig. 25.

Conclusions from the forecasting, the policy and the backcasting scenarios for road transport are:

- Under business-as-usual assumptions fuel demand and CO_2 emission from global transportation would more than double from 2000 to 2050 (Fulton and Eads, 2004, IEA, 2008b). Under various policy assumptions the fuel demand could increase by 50–190%, depending on economic development and the fuel efficiency of the vehicles. CO_2 emission may consequently increase between 40% and 130% compared to 2000, depending on policies pursued (IIASA-GGI, 2007; Borken-Kleefeld et al., forthcoming).
- The growing fuel demand cannot be supplied from oil alone. Gas- and coal-derived liquid synfuels could fill the gap. However, as they would have about twice as high upstream emissions as petroleum fuels, this would push CO_2 emissions (IEA, 2008b). If the production was however coupled with carbon capture and storage (CCS) technologies, synfuels could become climate friendly fuels (IIASA-GGI, 2007).
- Biofuels are the most promising medium term fuel offering much lower carbon emissions, definitely when produced from ligno-cellulose. This could become competitive at about US$ 50 per tonne CO_2 avoided. Electricity receives increasing attention, but major breakthroughs in battery technology are needed. Hydrogen is considered a niche fuel, i.e. barriers for their widespread application appear considerable until 2050 (IEA, 2008b; IIASA-GGI, 2007; Borken-Kleefeld et al., forthcoming).

5.5.2. Global non-CO_2 emission scenarios for road transportation

Scenarios for non-CO_2 emissions of road transportation globally were only developed by Fulton and Eads (2004) and Borken-Kleefeld et al. (forthcoming, Data can be accessed at www.ip-quantify.eu). Beyond assumptions about the development of fuel consumption and CO_2 emissions one needs assumptions about the potential development of the vehicle fleet mix in terms of vehicle categories (e.g. shift between light- and heavy-duty vehicles or between passenger cars and light vans), of vehicle sizes and – most importantly – of the future exhaust emission control technologies and regulations. Both, Fulton and Eads (2004) and Borken-Kleefeld et al. (forthcoming), assume that exhaust emission standards are

[4] IEA's World Energy Outlook 2008 (IEA, 2008a) is used as Reference Scenario, with data for 2050 extrapolated. See the discussion of Energy Technology Perspectives 2050, version 2008 (IEA, 2008b) in the text.

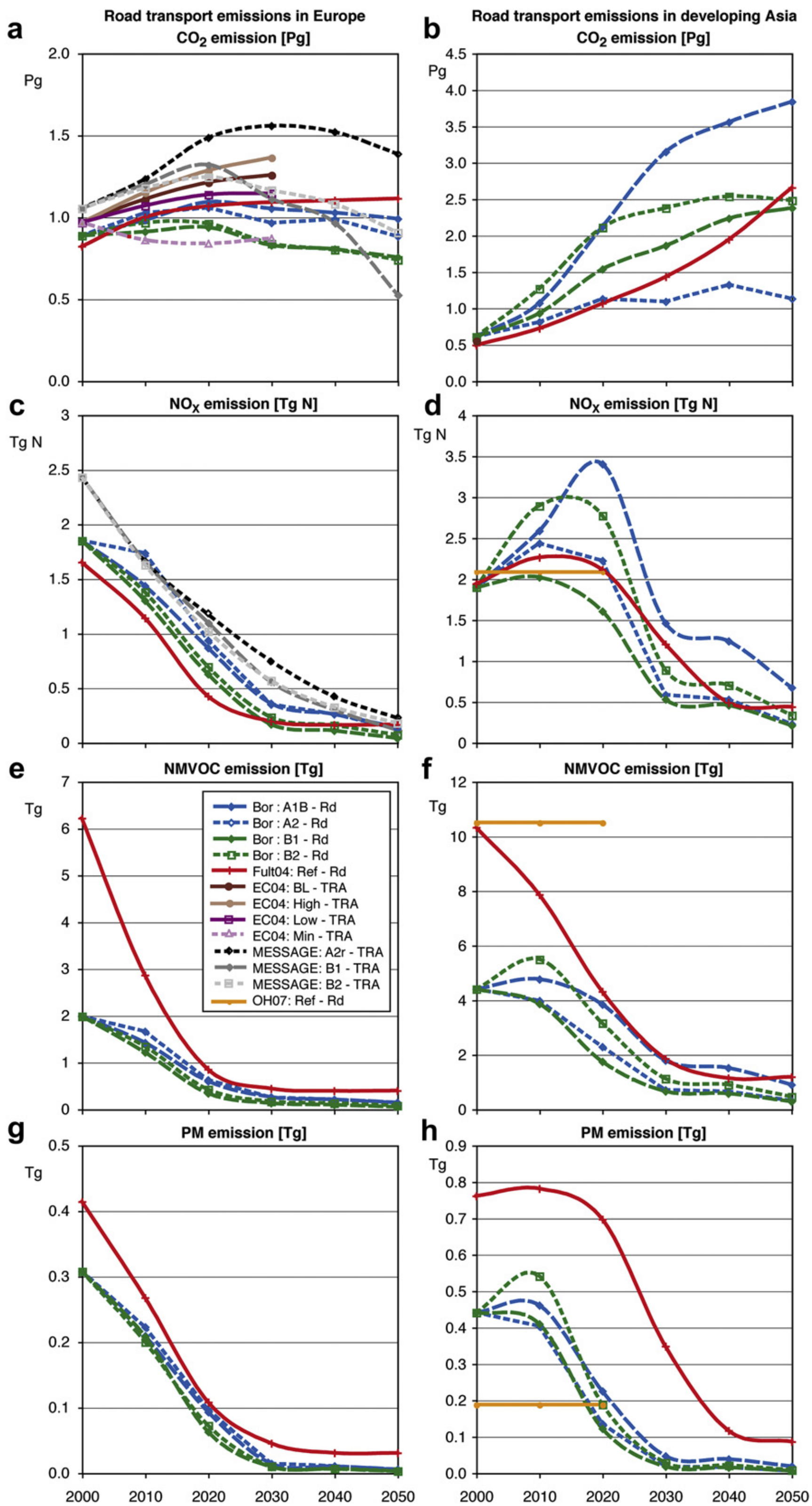

Fig. 25. Emission scenarios for road transportation in Europe and developing Asia. a and b) CO_2, c and d) NO_x, e and f) NMVOC, g and h) PM. They illustrate the developments in OECD regions and growing developing regions in general. Solid lines designate the IEA scenario family, dashed lines designate IPCC SRES type scenarios.

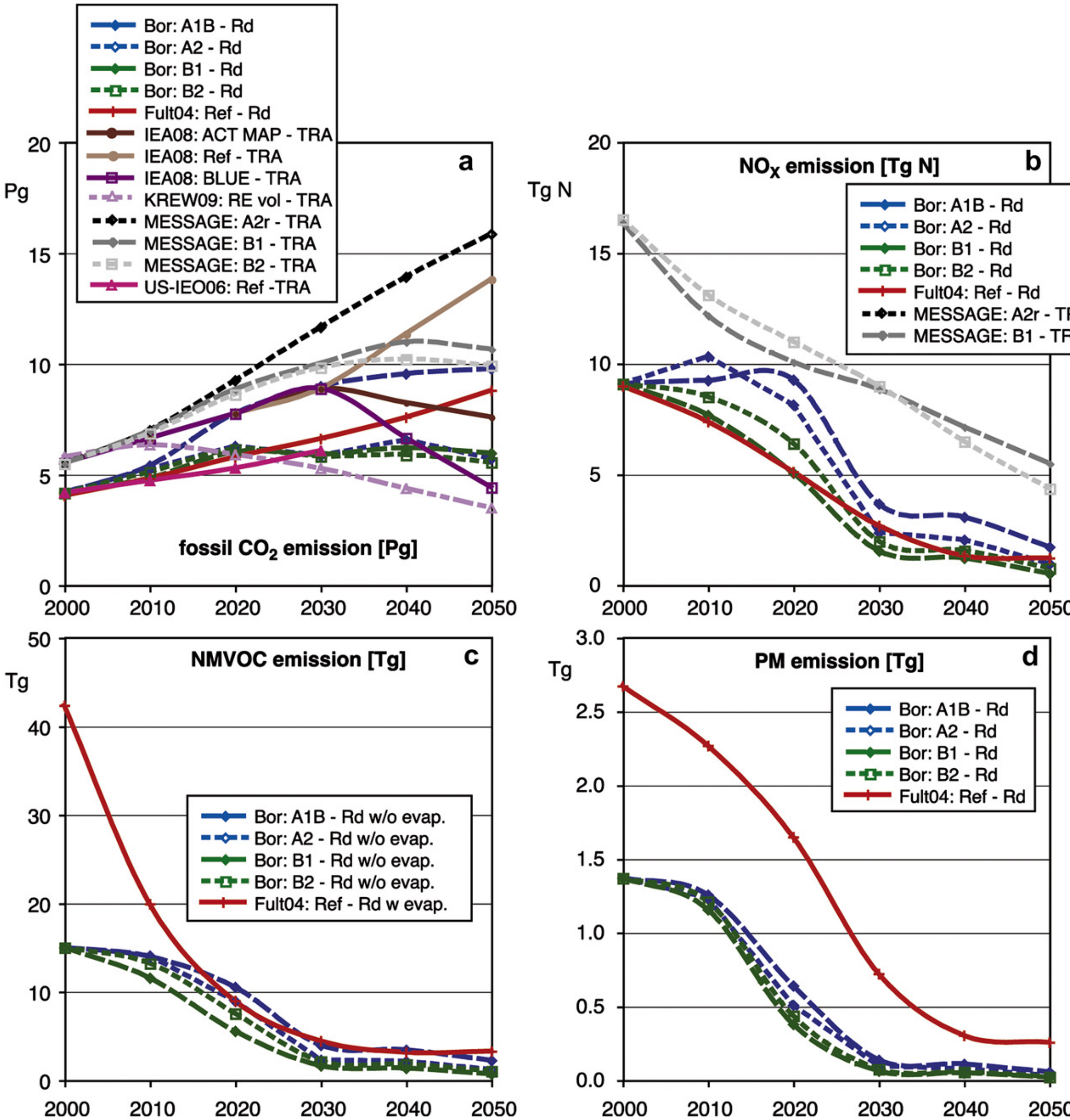

Fig. 26. Global total emissions for road transportation: a) CO_2 emissions (US-IEO06 covers all transport modes, i.e. approximately 20% more than just road transportation). IEO 2006 calculated from growth rate of fuel demand applied to Quantify y2000 CO_2 emissions. b) NOx, c) NMVOC emissions including or excluding evaporative emissions (Fulton and Eads, 2004; Borken et al., 2007), d) PM emissions. Solid lines designate the IEA scenario family, dashed lines designate IPCC SRES type scenarios. Scenarios are identified by author, scenario abbreviation and Rd/TRA, when data are for road transport or for the whole transport sector. Bor = Borken-Kleefeld et al.; Fult04 = Fulton & Eads 2004; IEA008 = IEA 2008b; Krew09 = Krewitt et al. 2009; MESSAGE = IIASA-GGI 2007; US-IEO06 = US-DoE 2006.

further tightened in the OECD regions; it is further assumed that these standards are then adopted in other world regions, notably in Asia where the transport growth is expected particularly strong. The scenarios differ in when exhaust emission controls are assumed to be introduced in the various world regions, how effective they will be in terms of standard level and its enforcement, and what vehicle categories they encompass beyond passenger cars.

According to all scenarios the global emissions of the non-CO_2 exhaust compounds (NO_x, NMVOC, PM) are assumed to be strongly decreased in the year 2050 (Fig. 26). The decrease relative to the year 2000 is between a factor of 5 and 60, depending on the assumed policy and compound. Similar decreases are expected for global emissions of CO, SO_2, PM_{10}, BC and OC. Sooner or later the improvements in vehicle exhaust emission control decouples the total emissions from the transport volume growth. The variation between scenarios is about a factor of 2 in the year 2050, at the significantly lower levels.

In general the change rates agree between Fulton and Eads (2004) and Borken-Kleefeld et al. (2008). However there are different assumptions about the emission developments in the first decades, notably for NO_x and PM. Fulton and Eads (2004) assume an immediate and continuous decline of all pollutants from the year 2000 onwards. Borken-Kleefeld et al. assume – in their transport interpretation of the SRES scenarios – a varied introduction and uptake of emission controls outside the OECD. For instance, the A1B scenario assumes the strongest growth in transport volume together with the introduction of more stringent emission controls worldwide. However for NO_x emissions this only balances the volume growth up to the year 2030, as the fleet renewal needs some time before it becomes effective. On the other hand, the scenario B1 assumes a tighter and more rapid introduction of emission controls throughout all world regions. This effectively decouples emissions from the transport growth and global emissions for NO_x could be at only half the level of scenario A1B. The span between the different scenarios, most pronounced for NO_x emissions, illustrates both the influence of different economic regimes as well as different policies concerning transport emission controls.

In summary, the key measure assumed in all scenarios is the further tightening of vehicle exhaust emission standards. Controling light-duty vehicles, but also mopeds and motorcycles, helps to contain and reduce emissions of CO and VOC emissions. In order to reduce emissions of NO_x, PM, and BC the heavy-duty vehicles need to be included in further emission controls. Technology appears ready for application; no scenario assumes major barriers or cost hurdles. However, a necessary enabling step is the further reduction of the sulphur contents of gasoline and diesel fuels in order for stringent exhaust emission control equipment to work properly. Reducing the sulphur contents to 50 ppm and ultimately below 10 ppm will require major investments in the refinery technology in many countries. Reduction of PM, BC and NO_x becomes effective through exhaust emission control. The control devices remove 90% and more of pollutants relative to unregulated emissions. However, while NO_x is indeed reduced, the NO_2 share emitted may increase at the expense of NO. Furthermore in the atmosphere reactions with ozone may lead to a stable or even higher NO_2 concentration in the atmosphere despite decreasing NO_x emissions. Therefore, it seems necessary to complement the NO_x limit value by a specific NO_2 emission limit value. Furthermore, effective enforcement appears key to ensure that measures taken are actually working.

5.5.3. *Mitigation costs for road transport*

There are a few estimates about the cost-effectiveness of mitigation options in the road transport sector. McKinsey and Co (2009) provide a global estimate for mitigation options in 2030; they calculate the mitigation potential and extra costs relative to World Energy Outlook 2007, which projected world crude oil prices at US$$_{2005}$ 60 per bbl in 2030 (IEA, 2007). Borken-Kleefeld et al. (2009) have calculated the mitigation options for the industrialised countries (signatories of the UNFCCC Kyoto-Protocol, Annex I) in 2020. Their baseline is the World Energy Outlook 2008 already discussed above, which projected world crude oil prices at US$$_{2005}$ 115 per bbl in 2030 (IEA, 2008a). The higher the oil price, the more economical investments in efficiency become. Both studies assume that investment costs for new or additional, more efficient technologies and low-carbon fuels are discounted over the lifetime of the equipment. The mitigation cost curves are presented in Fig. 27.

Both studies concur that many technologies, that would increase fuel efficiency and reduce CO_2 emissions pay for themselves by fuel savings over their lifetime. In fact net savings about outweigh net extra spending across the different vehicle categories. Further investments in improving the fuel efficiency of conventional combustion engines for cars and light trucks offer more than one third of the total mitigation potential for road transport while outweighing extra investments. Hybrid powertrains, including plug-in hybrids, offer a similar reduction potential. However, the related extra investments would become cost-effective at a carbon price of around 50 US$ per tonne CO_2 emitted. Hydrogen fuel-cell vehicles have not been considered important by 2020 or 2030 in either study.

For heavy-duty vehicles there is disagreement about the mitigation costs: McKinsey and Co (2009) assume that further improvements are not cost-effective at the projected (relatively low) fuel prices in 2030. Borken-Kleefeld et al. (2009) however identify a significant mitigation potential at negative net extra costs when discounted over the full vehicle life of about 15 years. This finding for trucks is in line with analysis by Bustnes (2006), Frey and Kuo (2007), Greszler (2007), Lutsey (2008), but it contrasts strongly with conventional wisdom that the trucking industry would have already optimised its efficiency potential to the maximum. This may be true when a return-of-investment within only one and a half to three years is required, as is the usual industry perspective; however this is not the perspective of policy making confronted with a global, long-term problem like climate change.

McKinsey and Co (2009) calculate a much large reduction potential than Borken-Kleefeld et al. (2009), for the following reasons: The reduction potential in 2030 must be much larger than in 2020, as twice as much time is available for the introduction of measures. Furthermore, McKinsey and Co (2009) include non-industrialised countries also, where the reduction potential is relatively large and cheap. In addition, McKinsey and Co (2009) include the mitigation potential by biofuels, that needs to be added to the data from Borken-Kleefeld et al. (2009). Lastly, the baseline emission level in 2030 is higher, hence bigger reductions can be realised at the same costs.

Conclusions from these analyses are:

- Many cost-effective technologies are already on the table and ready for implementation today. Their potential is estimated at about 20–30% reduction of CO_2 emissions below a 2030 baseline projection.
- The extra investments could be returned by fuel savings over the lifetime of many efficient technologies. In fact, total savings balance with extra investments across vehicle categories, both for 2020 and 2030.
- Most important and most cost-effective are improvements of the conventional internal combustion engines in light, medium and heavy trucks as well as in cars. The higher the oil-price or a carbon charge, the larger the cost-effective mitigation potential. This could be an important incentive for a more widespread and earlier application notably of hybrid powertrains.
- Significant mitigation options exist also for heavy-duty vehicle. Over the vehicle lifetime they can have significant cost-savings and even pay for themselves.
- The mitigation potential becomes significantly bigger over time as more efficient technologies penetrate more fully. However, this penetration will only have been effective, when action starts immediately. On the contrary, a delayed application will forego reduction potentials as it starts from a higher level.
- Low-carbon fuels, transportation demand management, buyers' shift to smaller vehicles and/or less travel, as well as improved logistics offer further mitigation potential beyond technological efficiency.

5.6. *Scenarios of future climate impacts and mitigation*

The climate impact of *future* emissions from (road) transport has, to our knowledge, only been calculated by Skeie et al. (2009). They use the emission scenarios developed within the *Quantify* project (Borken-Kleefeld et al., forthcoming), discussed above. They calculated the impact in terms of radiative forcing (RF) for all gases and compounds, i.e. including short-lived compounds and cooling

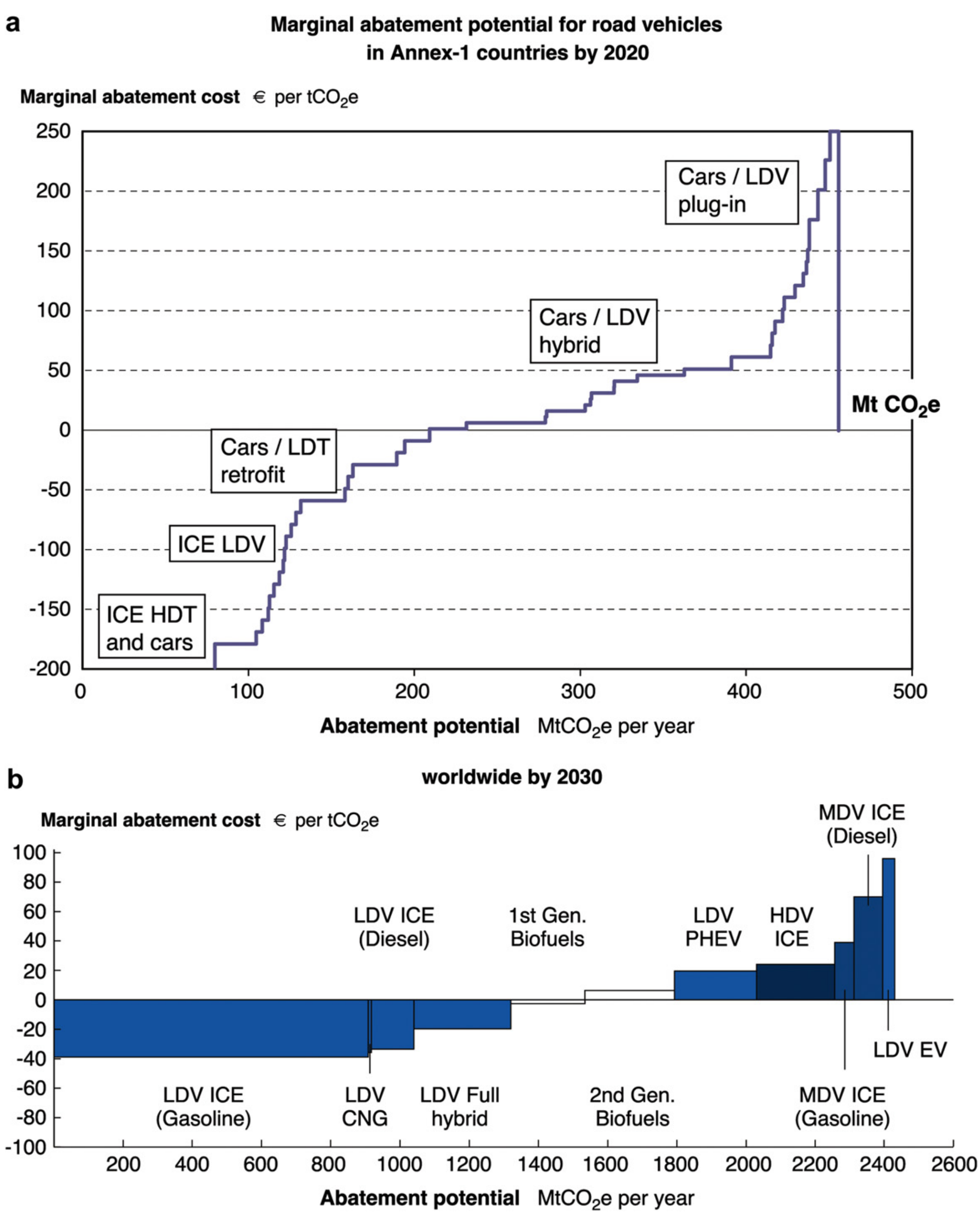

Fig. 27. Marginal abatement potential versus marginal abatement costs for road transport. a) Timeframe 2010–2020, payback over lifetime of equipment, sum over Annex-1 countries (industrialised countries) (Borken-Kleefeld et al., 2009). b) Timeframe 2010–2030, payback over lifetime of equipment, sum over world (McKinsey and Co, 2009).

effects, as well as the resulting temperature change. Key findings for road transport are:

- The radiative forcing in 2050 due to road transport emissions since 1900 is about 450 mW m^{-2} in A1B, the scenario with highest emission growth, and 325, 370 and 360 mW m^{-2} in scenarios A2, B1 and B2 respectively. This is a factor 1.9–2.5 higher than the radiative forcing due to emissions from 1900 to 2000 only (about 170 mW m^{-2} in year 2000). In other words, the climate impact in terms of radiative forcing will accelerate and intensify. Conf Fig. 28, left panel.
- The temperature increase in the year 2000 due to road transport's past emissions has been 0.08 °C, corresponding to about 11% total anthropogenic temperature change. Future emissions from global road transport lead to an additional temperature increase of 0.15 °C–0.11 °C in the high growth scenarios A1B and B1 respectively, and to about 0.10 in the low growth scenarios A2 and B2 by 2050. In fact, the same temperature increase as for the past 100 years will be attained within only 30–40 years, due to high growth in road transport. In 2100 road transport's emissions are expected to contribute another 0.30 °C–0.23 °C (scenarios A1B or B1), and 0.15 °C or 0.20 °C

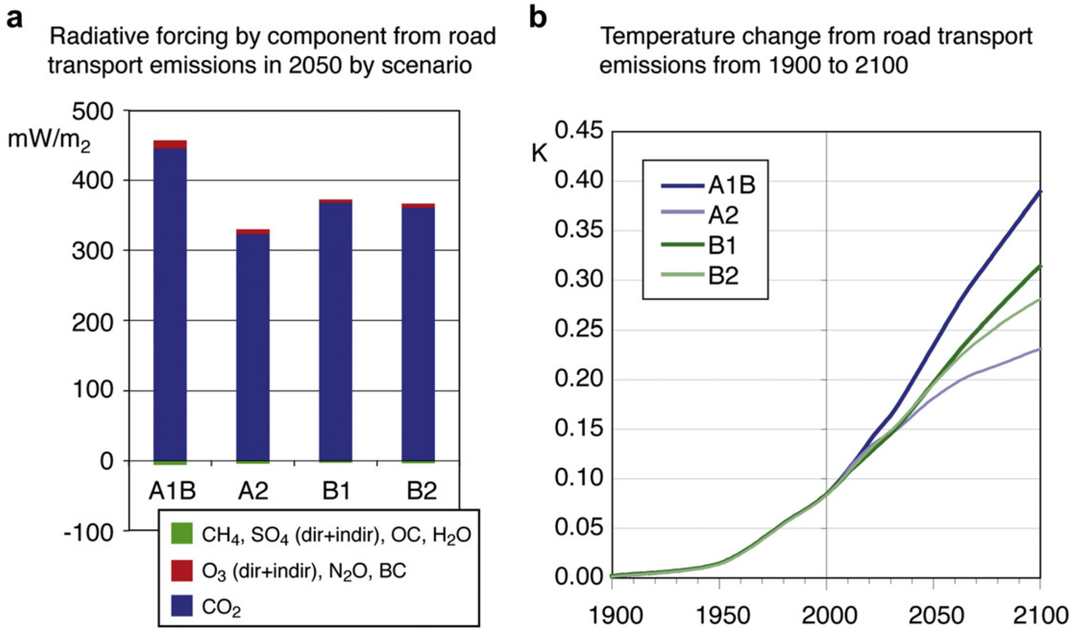

Fig. 28. Future climate impact from road transport emissions: a) Radiative forcing in 2050 according to scenarios; b) change in atmospheric temperature from 1900 to 2000 (due to historic emissions) and until 2100 according to scenarios (Data from Skeie et al., 2009).

(scenarios A2 or B2) respectively to global mean temperature. Hence, also for temperature change, the current emissions from transport have the highest impact on the future climate. Conf Fig. 28, right panel.

In all scenarios, road transport's emissions of non-CO_2 gases, notably ozone precursors and black carbon, are expected to decline by about one order of magnitude by 2050. Even if their reductions are 50% less ("delayed reduction") the future temperature change will only differ by 4% in 2050. This once again reinforces that the climate impact beyond 2030 is almost exclusively due to CO_2 emissions. Thus, as long as a reduction of non-CO_2 gases is ensured, mitigation can only be successful, if emissions of the long-lived gases, and notably CO_2, are reduced.

6. Conclusion

Emissions from land transport and in particular road vehicles significantly influence the atmospheric composition and the climate. Land transport currently contributes more than one fifth of the total anthropogenic carbon emissions in CO_2 equivalents, excluding land use change, about two thirds of which is emitted in OECD countries. The absolute emissions may still increase until the year 2050, with transport emissions from non-OECD countries growing quickly. The impacts on the atmosphere and climate depend on the species emitted and on the time scale considered.

6.1. Carbon dioxide

A strong, long-term climate signal comes from increasing CO_2 emissions. The impact will last for centuries. Road transport emitted about 4300 Tg carbon dioxide in 2000, corresponding to 72% of the CO_2 emitted by transport and 17% of the global 25.6 Pg CO_2 emitted from fossil fuel combustion and cement manufacture. The cumulative emissions since pre-industrial times translate into a radiative forcing of about 150 mW m^{-2} in 2000 for road traffic, compared to a total anthropogenic CO_2 forcing of 1660 mW m^{-2}. Road traffic's contribution is expected to grow significantly until the year 2050 in all forecasting scenarios. The future range of emissions may be between 6000 Tg and 11,300 Tg CO_2 per year unless a trend break happens. In the near future road transport will account for more than 20% of all annual human-induced CO_2 emissions. Over a 100-year horizon a one-year pulse of the emissions in 2000 would translate into a time-integrated radiative forcing of about 400 mW m^{-2} yr.

Direct emissions from rail transport are approximately 120 Tg CO_2 in 2000, resulting in 21 mW m^{-2} radiative forcing since pre-industrial times. A similar contribution comes from indirect emissions by electricity generation. Emissions from inland shipping are negligible on a global scale.

6.2. Halogenated compounds

A mid to long-term impact on radiative forcing comes from halogenated compounds, in particular HFCs and CFCs, released from mobile air conditioners (MAC). Presently, more than 50% of the worldwide automotive fleet is equipped with MAC. The 700 Tg CO_2-equivalents emitted as halocarbons in 2002 equal 17% of road transport's CO_2 emissions in 2000. The radiative forcing will decrease with shrinking banks of CFC-12, but it will remain relevant during the next decades. Existing HFCs and CFCs from MAC will furthermore continue to contribute to the decomposition of the ozone layer in the next decades. Until recently, stratospheric ozone depletion has contributed to a negative radiative forcing of climate (cooling tendency); however, this is expected to reverse in the next decades due to the decreasing chlorine concentration in the stratosphere. Hence, the positive radiative forcing in the troposphere by the growing use of the cooling agent HFC-134a is of higher relevance for the climate system.

6.3. Short-lived species

A short to mid-term climate impact comes from emissions of short-lived non-CO_2 gases as well as particles and particle precursors. These include nitrogen oxides (NO_x), carbon monoxide (CO), sulphur dioxide (SO_2), particles (PMs), black carbon (BC) and fugitive hydrocarbon emissions from fuel. Hydrocarbons and nitrogen oxides affect air quality and climate warming through the formation of the greenhouse gas ozone, of peroxyacetyl nitrate (PAN), and of hydroxyl radicals (OH), which, in turn, affect the equilibrium concentration of the greenhouse gas methane (CH_4). According to estimates deduced from smaller perturbations in models, emissions of NO_x and NMVOC from road traffic may contribute zonally averaged 2–6% to the formation of tropospheric ozone in the Northern Hemisphere during summer. On a regional scale ozone may increase by 3–5 ppb whereas around urban and industrial areas the impact may be larger. In parallel, OH can be increased by 2–4% in dense traffic regions in NH summer. In winter, the change of ozone and OH is small. Road traffic induced ozone can mix up to the tropopause in summer. The impact is similar to the one of aviation. On the other hand, since ozone induces also OH formation, the positive ozone forcing is partially offset by a reduced lifetime of methane.

For the year 2000 an ozone-related radiative forcing in the range of 50–54($\pm$11) mW m^{-2} has been calculated. A one-year pulse of the year 2000 emissions leads to a time-integrated RF of about 50 mW m^{-2} yr over 100 years.

A small positive radiative forcing comes from aerosols, primarily due to the effect of black carbon (32–44 mW m^{-2} for year 2000 emissions), which is partially counterbalanced by the impact of sulphate (-9.4 mW m^{-2} for year 2000 emissions).

In all world regions vehicle emission standards become stricter and fuel quality improves, with respect to sulphur, lead and aromatics contents. This has offset the effect from traffic growth and non-CO_2 emissions from road traffic have been declining in OECD countries. Non-OECD countries with high traffic growth might experience increasing emissions in the next two decades. Nonetheless, the global total emissions are assumed to decline significantly in all scenarios. Hence, one might conclude that the radiative forcing from short-lived species may not increase. Conversely, attention on the long-lived climate gases – expected to be increasing anyway – becomes even more important.

Short-lived traffic-related primary and secondary pollutants affect human health substantially. Most important are very fine particles (probably up to PM_1) and ozone. Increased ozone and fine particulates ($PM_{2.5}$) concentrations increase respiratory and cardiovascular symptoms and thus increase the risk for premature death. Concentrations of both PM and ozone have not declined in Europe since 1997 despite substantial cuts in emissions.

Emissions from road construction and vehicle and fuel production add to climate impact of traffic. In industrialised countries the construction and maintenance of the road infrastructure may contribute up to 20% of CO_2 emissions from the tailpipe. The production of a mid-size car may result in about 12% of the total CO_2 emissions from driving. Production and supply of gasoline and diesel adds about 15% to tailpipe CO_2 emissions from fuel combustion. With increasing diversity in fuels these upstream emissions become more important. Biofuels are available but are also subjects to various objections, for example if the same plant is used for the fuel and food industry. Their emissions strongly depend on the feedstock and its yield, the production process and the previous of alternative land use. The currently best of first generation biofuels have net savings of about 20–30% CO_2 equivalents relative to well-to-wheel emissions from petroleum based fuels. The second generation biofuels are expected to have higher net savings but will not be commercially available before 2020. Emissions for electricity or – in a potential future – hydrogen entirely depend on the primary energy mix and the production efficiency. Only when produced from low-carbon sources, potentially also including nuclear power and gas, or coupled with carbon capture and storage, these fuels offer a CO_2 benefit over petroleum based fuels. Reducing the net carbon intensity (per energy contents) of the fuels is one major area for mitigating climate change from the transport sector. The risk is however, that growing fuel demand is met with unconventional oil or coal-derived fuels that have much higher upstream CO_2 emissions, besides other environmental drawbacks.

Another major area for mitigation is to drastically increase vehicle fuel efficiency. The conventional combustion engine still offers significant efficiency potentials at relatively low prices for both, passenger and freight vehicles. A hybridisation of the powertrain can further increase the efficiency notably under urban driving conditions. If a combination of several existing technologies would be applied in the fleet, savings of 20–30% of CO_2 emissions could be achieved in OECD countries by 2030 without extra costs. However, markets alone will not deliver these reductions. Reducing vehicle power and weight would be straightforward, rather cheap options to downsize energy demand and thus emissions notably from light-duty vehicles. Overall a factor 4 increase in fuel efficiency is technically possible for light-duty vehicles. However, customer acceptance without incentives, penalties or regulations is questionable. The risk is that customers in industrialised countries are unwilling to use smaller vehicles, while customers in growing economies are aspiring bigger cars. Further down the time horizon, yet considered important to both improve efficiency and to allow low-carbon fuels, is electric traction, either powered by a battery or by a fuel cell. This however requires still major improvements of the battery in terms of cost reduction, durability, capacity and weight or major investments in a hydrogen supply infrastructure.

From today's point of view, however, all these technologies can only reduce the expected growth. Depending on which technologies are applied this growth is estimated to range between 40% and 130%. An absolute reduction of CO_2 emissions, the most important climate mitigation measure for the transport sector, will need stronger interventions. Only scenarios that assume less transport arrive at overall emission reductions. Effective mitigation must address the factors for transport growth in order to contain passenger and freight transport volumes.

Thus, if the transport sector shall contribute to meeting climate mitigation objectives a combination of all measures is necessary: strongly increasing the vehicles' fuel efficiency, reducing the carbon contents of the fuels, and reducing total transport volumes.

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Appendix A

Reports and assessments

Up to now, there is no comprehensive scientific assessment of ground transport effects on climate change available, including emission inventories, climate impact modelling and mitigation options. Fuglestvedt et al. (2008) present the first comprehensive analysis of radiative forcing arising from the different transport modes, for today as well as in an cumulative overview of the past.

The private industry involved in road traffic published the study "Mobility 2030" as final report of the Sustainable Mobility project of the World Business Council for Sustainable Development (http://www.wbcsd.org/). An overview of land transport challenges is presented and a forecast model has been developed in cooperation with IEA (SMP/IEA transport model, Fulton and Eads, 2004), discussed also in the emission part of this assessment.

IPCC Climate Change (2007a,b,c) does not discuss the role of emitting sectors in detail, but gives an analysis of mitigation options in the transport sector in the WG III report.

Transport issues in Europe are regularly investigated by the European Environment Agency in the EEA transport series (http://www.eea.europa.eu/themes/transport/), e.g. the recent EEA report No.1-2007 "Transport and environment: on the way to a new common transport policy". EEA observed a general increase in transport in Europe, for passenger transport slightly less than the increase in the gross domestic product GDP, for freight clearly more. Road freight transport growth in the EU is projected to continue, resulting in an increase in energy demand of more than 15% between 2000 and 2020 (De Ceuster et al., 2005). Therefore, additional policy initiatives and instruments are demanded.

Policy options are discussed in the European Commission's 2001 White Paper on European transport policy (European Commission WP, 2001). This listed around 60 policy initiatives which were later endorsed by subsequent European Council meetings, including not only climate and health impacts, but also traffic management, economic and safety aspects. WP 2001 also links emissions and infrastructure measures and considers political mitigation measures as harmonisation of fuel taxation for commercial users and alignment of the principles for charging for infrastructure use. A mid-term review (MTR) of the White Paper has been presented in 2006 by the European Commission taking stock of what has been achieved over the past five years and proposes a number of new actions to further improve the European transport system.

The EC Impact Assessment of the Thematic Strategy on Air Pollution and the Directive on "Ambient Air Quality and Cleaner Air for Europe" (European Commission, 2005b) include legislative proposals related to transport. In the near future, they shall achieve the reduction of the transboundary component of urban background concentration of $PM_{2.5}$. These measures include reviewing emissions limits for light- and heavy-duty vehicles (e.g. to go beyond current Euro standards) and revision of the National Emission Ceilings for 2015 or 2020 in order to reduce urban background concentrations of $PM_{2.5}$.

Recent and ongoing research

The European Commission supports many activities, programmes and initiatives dealing with air quality and climate change.

A significant improvement in our understanding of transport's impacts on climate and ozone is expected from the EC FP6 integrated project *Quantify* (www.pa.op.dlr.de/quantify/). This project is dealing with quantifying impacts from individual transportation sectors like aviation, shipping and road transport. It is the first comprehensive attempt not only to quantify these impacts in global climate model (GCM) runs, but to account for the effects of chemical non-linearity in dilution of the emission behind the exhausts as well as to include metrics for simpler emission reduction assessments.

The European "Clean Air for Europe" Programme (CAFE, http://ec.europa.eu/environment/air/cafe) aims to develop a long-term, strategic and integrated policy advice to protect against significant negative effects of air pollution on human health and the environment. A new phase of CAFE, the implementation of the Thematic Strategy on Air Pollution, started in September 2005.

The Cooperative Programme on the Monitoring and Evaluation of Long-range Transmission of Air Pollutants in Europe (EMEP) has already been running for a long time under the Convention on Long-range Transboundary Air Pollution (http://www.unece.org/env/lrtap/) in order to support international cooperation to solve transboundary air pollution problems. EMEP includes also Northern America and recently even addresses long-range transport of the whole northern hemisphere through the Hemispheric Transport of Air Pollution (HTAP) Task Force (http://www.htap.org/).

A cluster of European projects focussed on the investigation of vehicles emissions: *ARTEMIS* (Assessment And Reliability Of Transport Emissions And Inventory Systems), *COST 346* (Emissions and Fuel Consumption from Heavy-Duty Vehicles http://www2.vito.be/cost346/) and *PARTICULATES* (Characterisation of Exhaust Particulate Emissions from Road Vehicles).

ARTEMIS computes emissions at a low spatial scale and investigates the behaviour of vehicles in driving cycles. The results, which are implemented in a European emission model for light vehicles, tell that different approaches in emissions inventories and the unstable behaviour of vehicles with emission reduction devices (catalytic converters, particles filters) lead to a high uncertainty about what a single car emits. ARTEMIS states for example that there is quite contrasted behaviour between Diesel (rather sensitive to speed and stop parameters) and gasoline cars (rather sensitive to accelerations).

COST 346 focussed on similar work for heavy-duty vehicles. It gave an overview of emission data, developed an engine map database, used the datasets in an emission model and estimates uncertainties. For the EURO 4 and 5 emission standards, COST 346 expects common test bed analysis to become less reliable, since the engine performance depends more and more strongly on the control system of the specific vehicle.

PARTICULATES investigated the progress and potentials in the reduction of particulate matter. A major step forward is seen in the control of automotive particulate emissions is through the application of diesel particulate filters and sulphur-free fuels (10 mg kg^{-1} max Sulphur content). PARTICULATES focussed mainly on diesel light-duty and heavy-duty vehicles, but emphasises for example also that the role of two wheelers in less developed countries may be underestimated.

The potential use of alternative fuels have been studied in European projects like *TRIAS* (TRIAS = Sustainability Impact Assessment of Strategies Integrating Transport, Technology and Energy Scenarios http://www.isi.fhg.de/trias/) and *HyWays* (HyWays A European Hydrogen Energy Roadmap http://www.hyways.de):

TRIAS presents different scenarios of fuel mixes for the future and discusses the potentials in particular of biofuel. HyWays states that strong policy support is needed in order to achieve a fleet of 15 million fuel cell driven vehicles in Europe by 2030, even extreme policy support for the upper limit of 50 million vehicles.

Since such estimates are very uncertain they are at present not yet reflected in climate impact modelling. Therefore, long-term potentials for climate change mitigation thanks to sustainable mobility are still an unknown.

Appendix B

Major acronyms and abbreviations:

ACEA Association des Constructeurs Européens d'Automobiles
ACIA Arctic Climate Impact Assessment
ADMS urban pollution model
AOT Accumulated Ozone exposure Thresholds
ARTEMIS Assessment And Reliability Of Transport Emissions And Inventory System

ATTICA Assessment of Transport Impacts on Climate Change and Ozone Depletion
BC Black Carbon
BEACON Building Environmental Assessment Consensus on the transeuropean transport network
CAFE Clean Air for Europe programme
CDIAC Carbon Dioxide Information Analysis Center
CER Community of European Railway and Infrastructure Companies
CICERO Centre for International Climate and Environmental Research (Norway)
CNG Compressed Natural Gas
CO_2-eq carbon dioxide equivalent
CONCAWE European Oil Company Organisation for Environment, Health and Safety (Belgium)
COPD chronic obstructive pulmonary disease
CORINAIR European Union Emission Inventory Programme
COST 346 Emissions and Fuel Consumption from Heavy-Duty Vehicles
COST 350 Integrated assessment of environmental impact of traffic and transport infrastructure
CRT continuous regeneration diesel particle filters
DG Directorate General
DG TREN Directorate General for Transport and Energy
DLR Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DoE US-Department of Energy
DU Dobson Unit
EC European Commission
ECMWF European Centre for Medium-Range Weather Forecasts (Reading, UK)
EDGAR Environmental Database for Global Atmospheric Research
EDC European drive cycle
EEA European Environment Agency
EEV Enhanced Environmentally-friendly Vehicle
EIONET European Environment Information and Observation Network
EMEP European Monitoring and Evaluation Programme
E39C DLR L39 coupled chemistry-climate model
EU European Union
EUCAR European Council for Automotive Research
EPA US-Environmental Protection Agency
FP6 Sixth Framework Programme for Research
GCM General Circulation Model
GDP gross domestic product
GHG Greenhouse Gas
GTL Gas to Liquids
GTP Global Temperature Change Potential
GTP_{20} Global Temperature Change Potential with a 20-year time horizon
GTP_{50} Global Temperature Change Potential with a 50 year time horizon
GTP_{100} Global Temperature Change Potential with a 100-year time horizon
GWP Global Warming Potential
GWP_{100} Global Warming Potential with a 100-year time horizon
HDV heavy-duty vehicle
HTAP Task Force on Hemispheric Transport of Air Pollution
ICE internal combustion engine
IEA International Energy Agency
IEO International Energy Outlook
IIASA International Institute for Applied Systems Analysis (Austria)
IPCC Intergovernmental Panel on Climate Change
JRC Joint Research Centre
LCA life-cycle analysis
LDV light-duty vehicles
LES Large Eddy Simulation
LMDz Laboratoire de Météorologie Dynamique GCM
LRTAP Long-Range Transboundary Air Pollution
LSCE/IPSL Laboratoire des Sciences du Climat et l'Environnement (France)
MAC mobile air conditioners
MILAGRO Megacity Initiative: Local and Global Research Observations
MOST Mobility Management Strategies for the next decades
MTR mid-term review
NEDC New European Drive Cycle
NG Natural Gas
NH northern hemisphere
NiMH nickel metal hydride
NMVOC Non-Methane Volatile Organic Compounds
NPRI National Pollutant Release Inventory
NRC National Research Council
OC Organic Carbon
OECD Organisation for Economic Co-operation and Development
PAH polyaromatic hydrocarbons
PARTICULATES Characterisation of Exhaust Particulate Emissions And Inventory System
PBL planetary boundary layer
PEMFC polymer electrolyte membrane fuel cells
PM Particulate Matter
$PM_{0.1}$ Particulate Matter (diameter less than 0.1 μm)
$PM_{2.5}$ Particulate Matter (diameter less than 2.5 μm)
PM_{10} Particulate Matter (diameter less than 10 μm)
QUANTIFY Quantifying the Climate Impact of Global and European Transport Systems
RF Radiative Forcing
RR relative risk
RSST Rapid Science Synthesis Team
SAE Society of Automotive Engineers
SCR Selective Catalytic Reduction
SEA Strategic Environmental Assessment
SLC Super-Light Car
SOA Secondary Organic Aerosol
SRES Special Report on Emissions Scenarios
SROC Special Report on Safeguarding the Ozone Layer and the Global Climate System
SUTRA Sustainable Urban Transport Project
TERM Transport and Environment Reporting Mechanism (EEA)
TRANSLAND Integration of Transport and Land Use Planning
TRENDS Transport and Environment Database System
TRIAS Sustainability Impact Assessment of Strategies Integrating Transport, Technology and Energy Scenarios
3-D three-dimensional
UIC Union International de Chemins de Fers
UNFCCC United Nations Framework Convention on Climate Change
US United States
US-DoT United States – Department of Transportation
US-DoE United States – Department of Energy
UTLS Upper Troposphere–Lower Stratosphere
VOC Volatile Organic Compound
WBCSD World Business Council for Sustainable Development
WG working group
WMO World Meteorological Organization
WHO World Health Organization
WSDA Washington State Department of Agriculture

Appendix C

Units

SI (Systeme Internationale) units:

Special names and symbols for certain SI-derived units:

Special names and symbols for certain SI-derived units:

Physical quantity	Name of unit	Symbol
length	metre	m
mass	kilogram	kg
time	second	s
thermodynamic temperature	kelvin	K
amount of substance	mole	mol

Fraction	Prefix	Symbol	Multiple	Prefix	Symbol
10^{-1}	deci	d	10	deca	da
10^{-2}	centi	c	10^{2}	hecto	h
10^{-3}	milli	m	10^{3}	kilo	k
10^{-6}	micro	μ	10^{6}	mega	M
10^{-9}	nano	n	10^{9}	giga	G
10^{-12}	pico	p	10^{12}	tera	T
10^{-15}	femto	f	10^{15}	peta	P

Appendix D

Physical quantity	Name in SI unit	Symbol for SI unit	Definition of unit
force	newton	N	kg m s^{-2}
pressure	pascal	Pa	kg m^{-1} s^{-2} (=N m^{-2})
energy	joule	J	kg m^{2} s^{-2}
power	watt	W	kg m^{2} s^{-3} (=J s^{-1})
frequency	hertz	Hz	s^{-1} (cycles per second)

Some chemical symbols used:

Physical quantity	Name of unit	Symbol for unit	Definition of unit
length	Ångstrom	Å	10^{-10} m = 10^{-10} cm
length	micron	μm	10^{-6} m
area	hectare	ha	10^{-4} m^{2}
force	dyne	dyn	10^{-5} N
pressure	Bar	bar	10^{5} N m^{-2} = 10^{5} Pa
pressure	millibar	mb	10^{2} N m^{-2} = 1 hPa
mass	tonne	t	10^{3} kg
mass	gram	g	10^{-3} kg
column density	Dobson Units	DU	2.687×10^{16} molecules cm^{-2}

Non-SI units	Name of unit
°C	degree Celsius (0°C = 273 K approximately)
ppmv	parts per million (10^{6}) by volume
ppbv	parts per billion (10^{9}) by volume
pptv	parts per trillion (10^{12}) by volume
yr	Year
ky	thousands of years
bp	before present
Units of mass which have come into common usage	
GtC	gigatonnes of carbon (1 GtC = 3.7 Gt carbon dioxide)
PgC	petagrams of carbon (1 PgC = 1 GtC)
MtN	megatonnes of nitrogen
TgC	teragrams of carbon (1 TgC = 1 MtC)
Tg(CH_4)	teragrams of methane
TgN	teragrams of nitrogen
TgS	teragrams of sulphur

Al	aluminium
Ca	calcium
Ca^{2+}	calcium ion
CFC	chlorofluorocarbon
CFC-12	dichlorodifluoromethane
Cl	atomic chlorine
Cl^{-}	chlorine ion
ClO	chlorine monoxide
$ClONO_2$	chlorine nitrate
ClOOCl	chlorine peroxide
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
Cr	chromium
Cu	copper
Fe	iron
H	atomic hydrogen
H_2	molecular hydrogen
HC	hydrocarbon
HCHO	formaldehyde
HFC	hydrofluorocarbon
HFC-134a	CF_3CH_2F
HFC-152a	CH_3CHF_2
HCl	hydrogen chloride
HO_2	hydroperoxyl
H_2O	water
K	potassium
K^{+}	potassium ion
Mg	magnesium
Mg^{2+}	magnesium ion
Mn	manganese
Na^{+}	sodium ion
Ni	nickel
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides (NO + NO_2)
N_2O	nitrous oxide
$O(^1D)$	atomic oxygen (first excited state)
O_2	molecular oxygen
O_3	ozone
OH	hydroxyl radical
P	phosphorus
PAN	peroxyacetyl nitrate
Pb	lead
Pb^{+}	lead ion
POM	polyoxymethylene
S	atomic sulphur
Si	silicon
SO_2	sulphur dioxide
Ti	titanium
VOC	volatile organic compounds
Zn	zinc

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